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(54) **METHOD FOR PACKAGE-ON-PACKAGE ASSEMBLY WITH WIRE BONDS TO ENCAPSULATION SURFACE**

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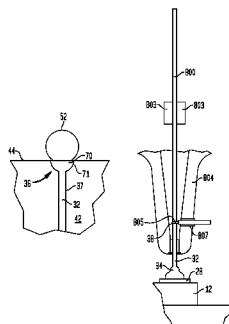
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(57) **ABSTRACT**

A microelectronic assembly (10) includes a substrate (12) having a first and second opposed surfaces. A microelectronic element (22) overlies the first surface and first electrically conductive elements (28) can be exposed at at least one of the first surface or second surfaces. Some of the first conductive elements (28) are electrically connected to the microelectronic element (22). Wire bonds (32) have bases (34) joined to the conductive elements (28) and end surfaces (38) remote from the substrate and the bases, each wire bond defining an edge surface (37) extending between the base and the end surface. An encapsulation layer (42) can extend from the first surface and fill spaces between the wire bonds, such that the wire bonds can be separated by the encapsulation layer. Unencapsulated portions of the wire bonds (32) are defined by at least portions of the end surfaces (38) of the wire bonds that are uncovered by the encapsulation layer (42).

**4 Claims, 19 Drawing Sheets**



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FIG. 1

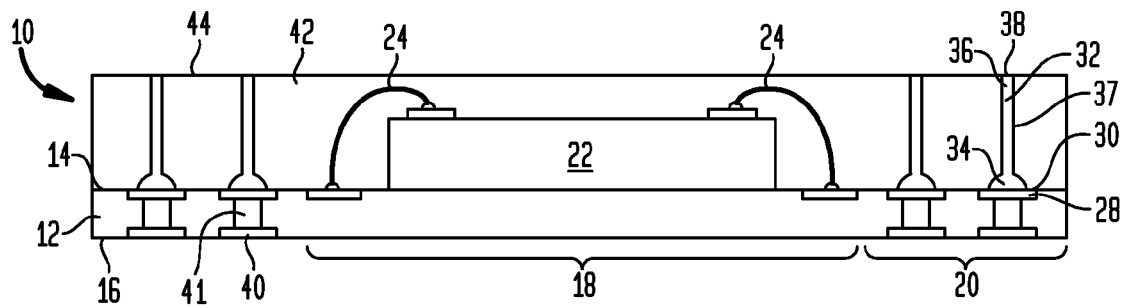


FIG. 2

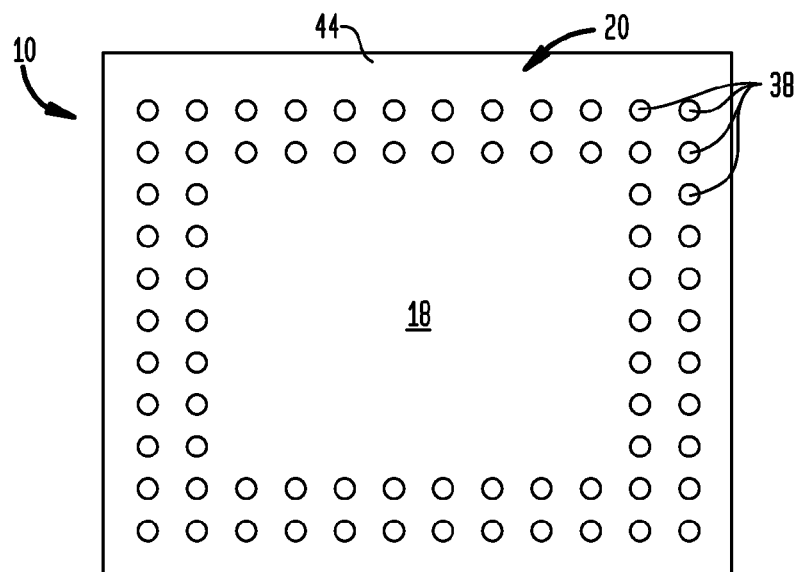


FIG. 3

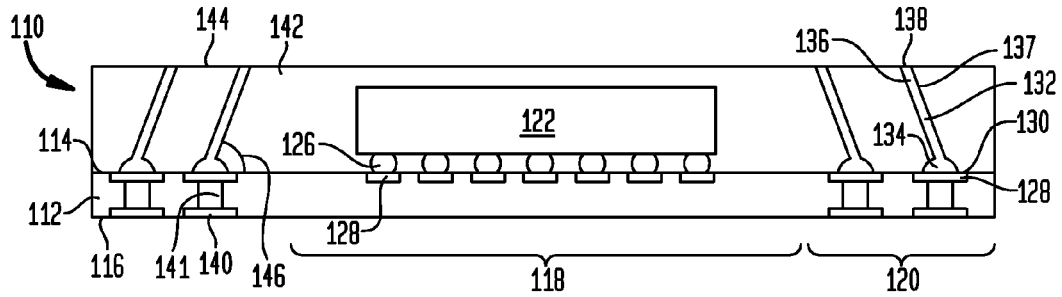


FIG. 4

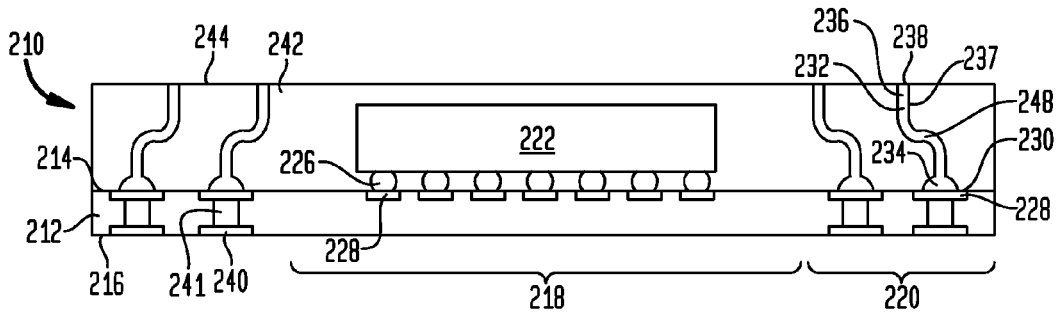


FIG. 5

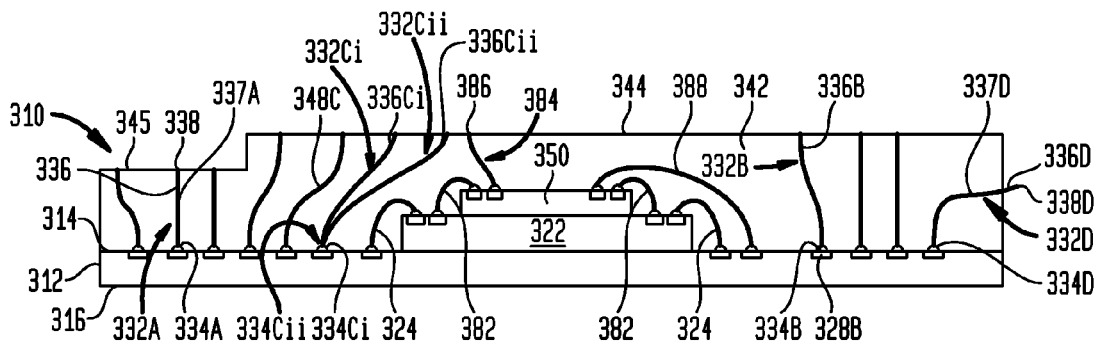




FIG. 6

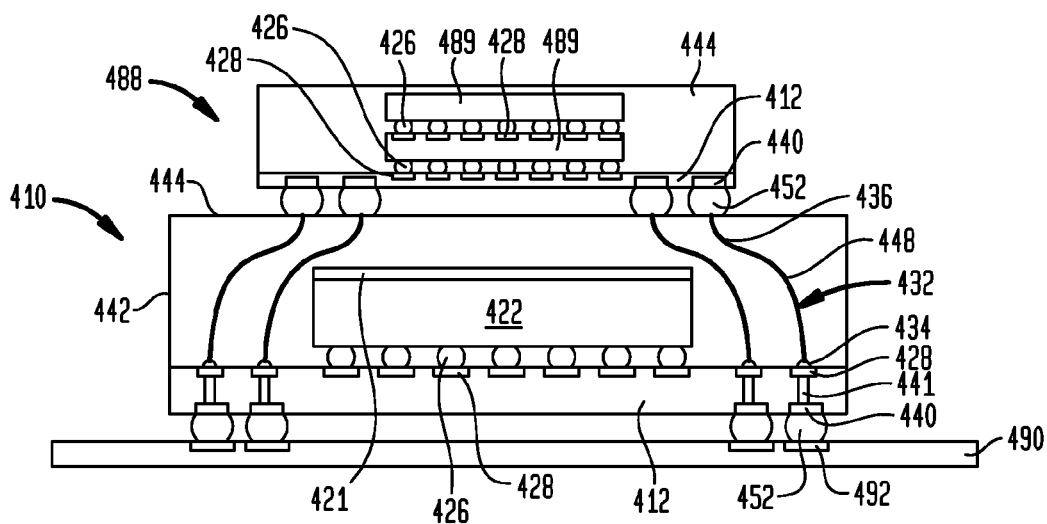
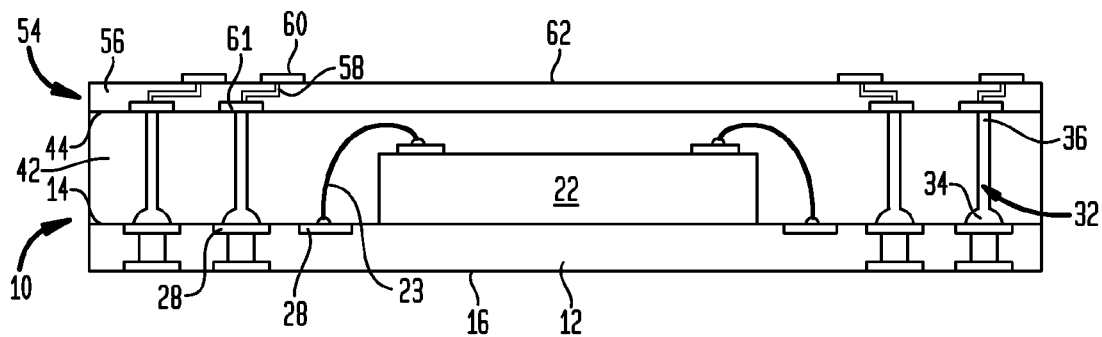
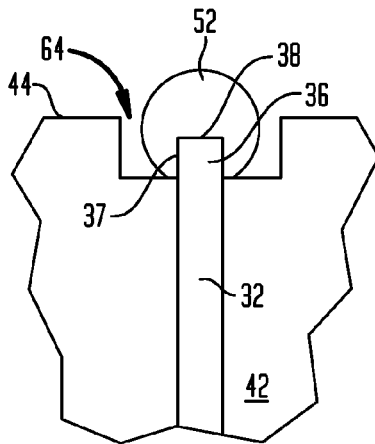


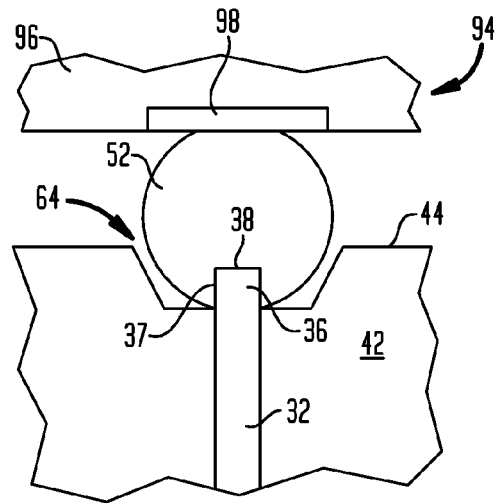
FIG. 7



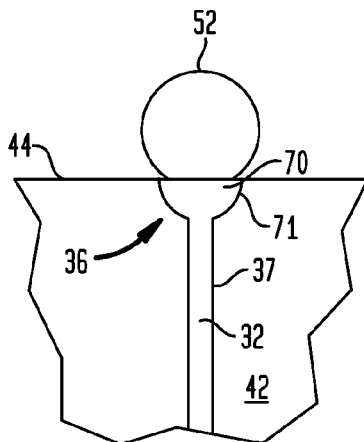
**FIG. 8A**



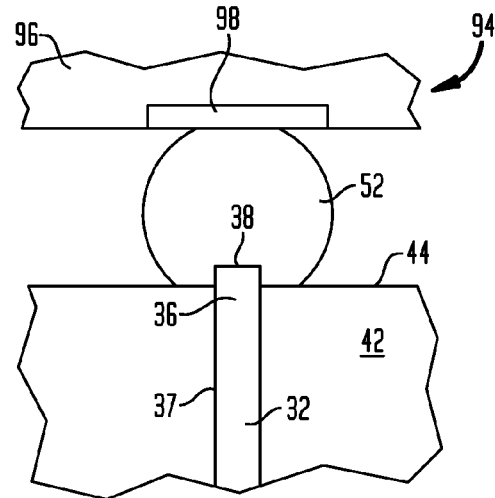
**FIG. 8B**



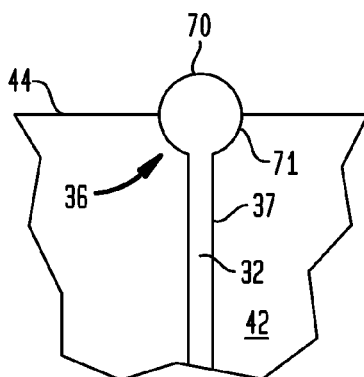
**FIG. 8C**



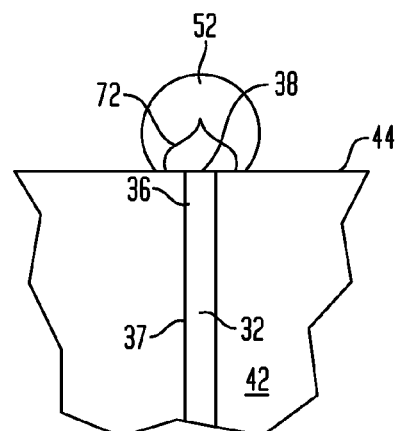
**FIG. 8D**



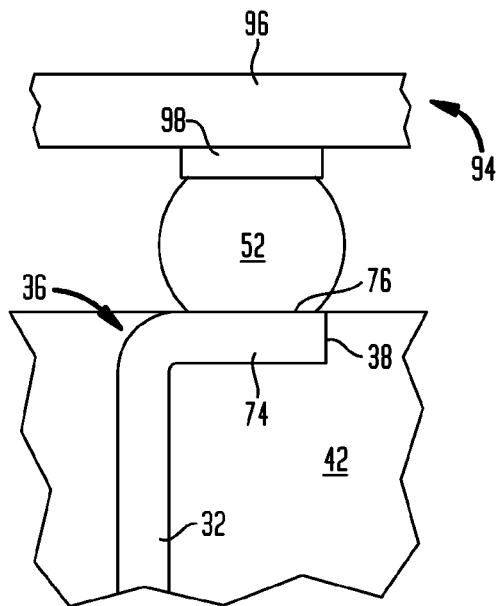
**FIG. 8E**



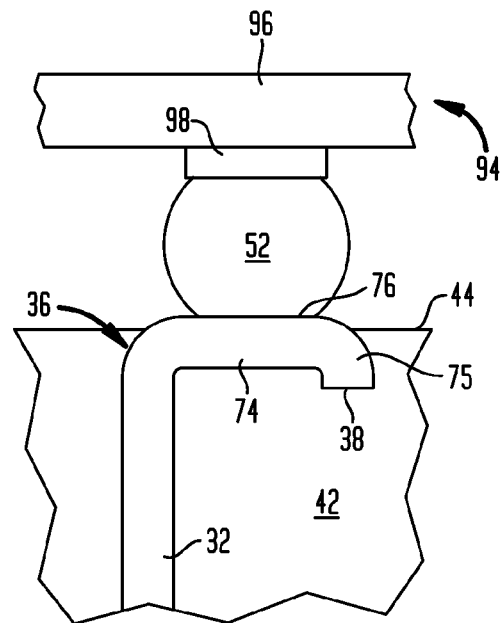
**FIG. 9**



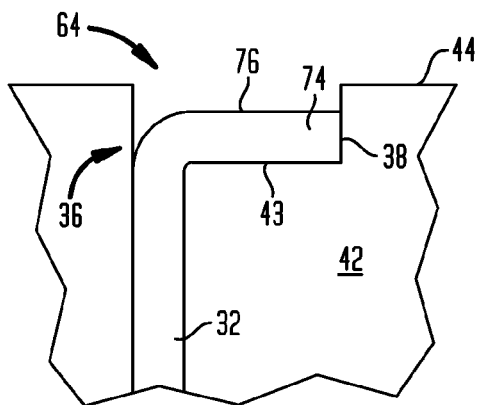
**FIG. 10A**



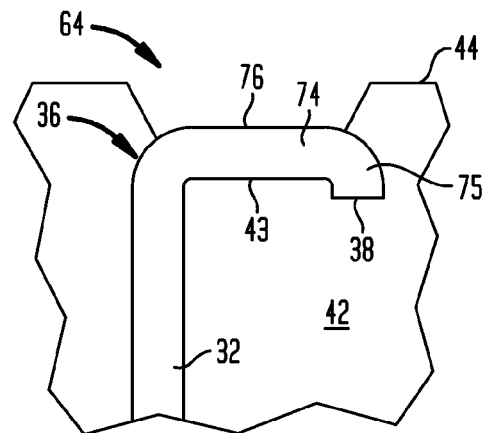
**FIG. 10B**



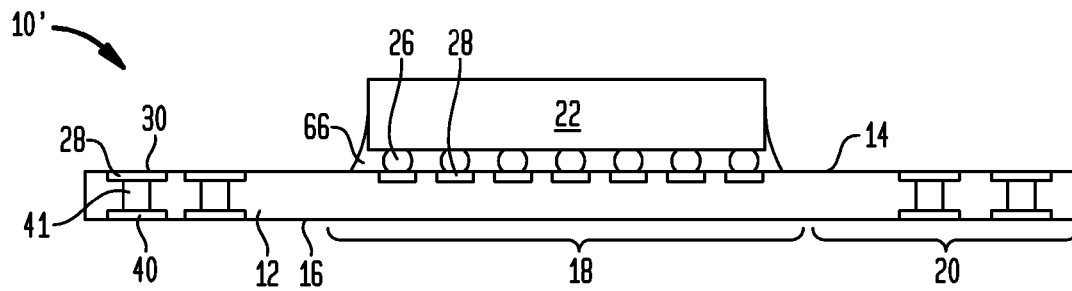
**FIG. 10C**



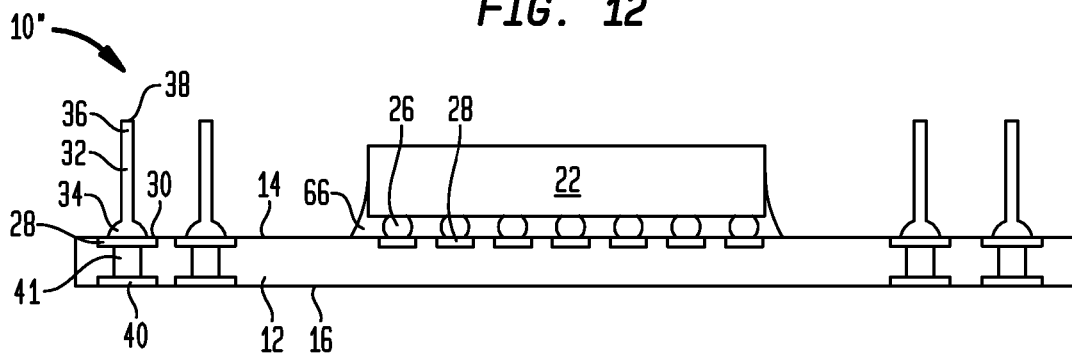
**FIG. 10D**



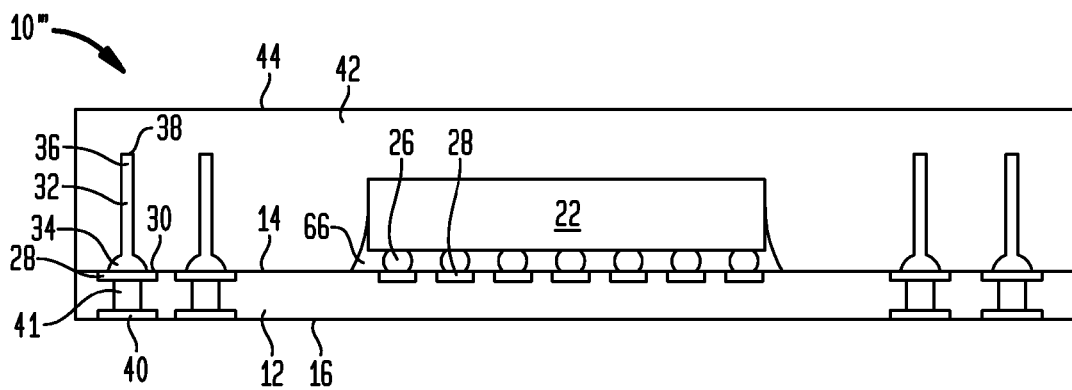
**FIG. 11**



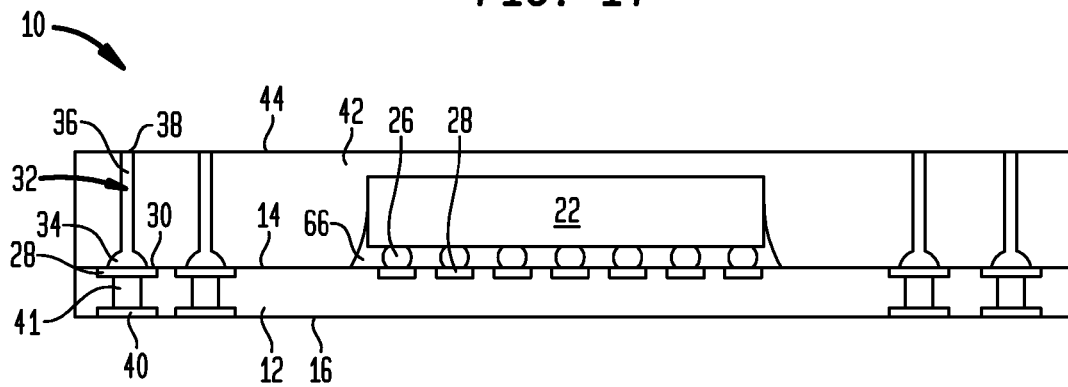
**FIG. 12**



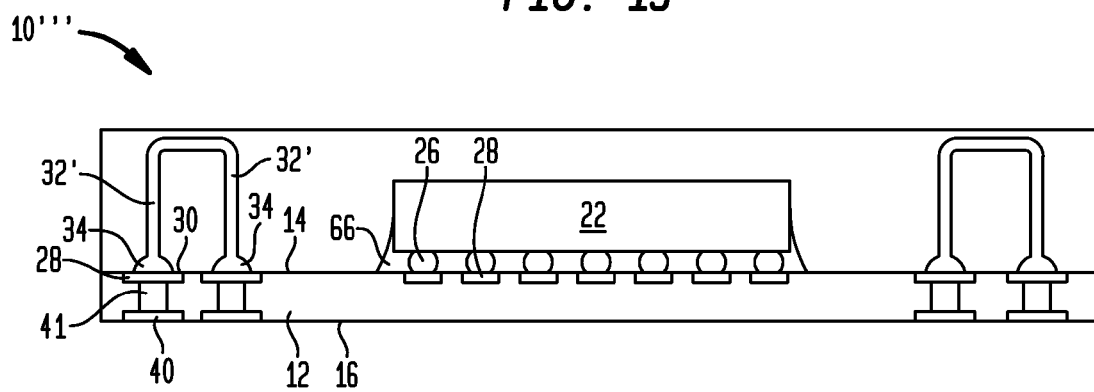
**FIG. 13**



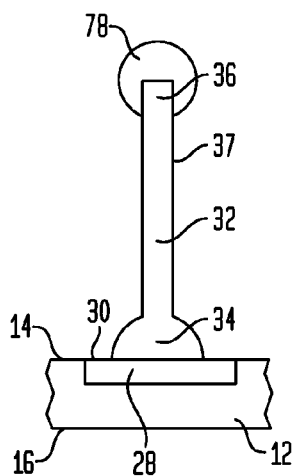
**FIG. 14**



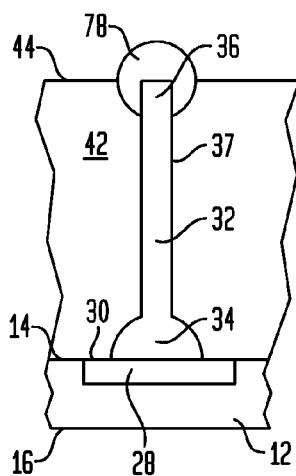
**FIG. 15**



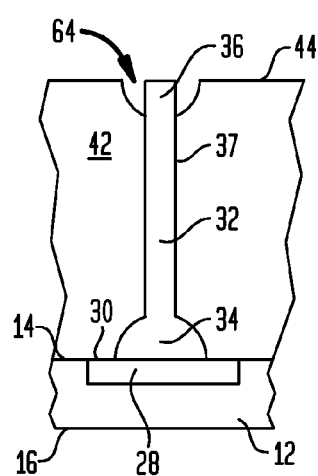
**FIG. 16A**



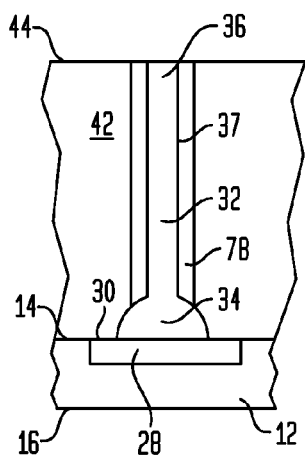
**FIG. 16B**



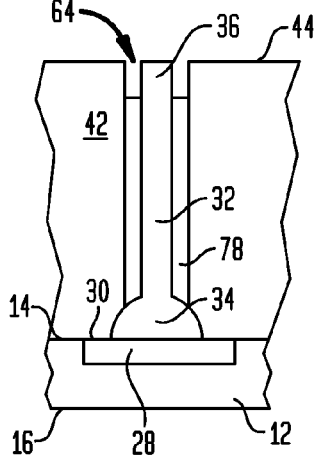
**FIG. 16C**



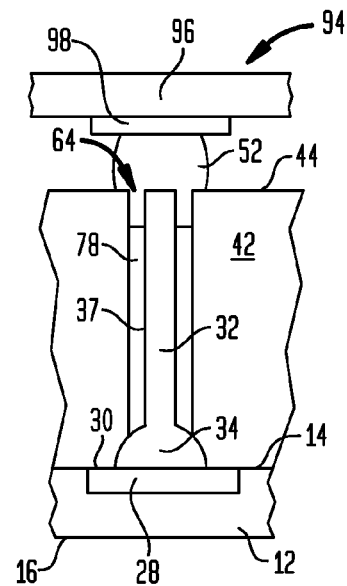
**FIG. 17A**



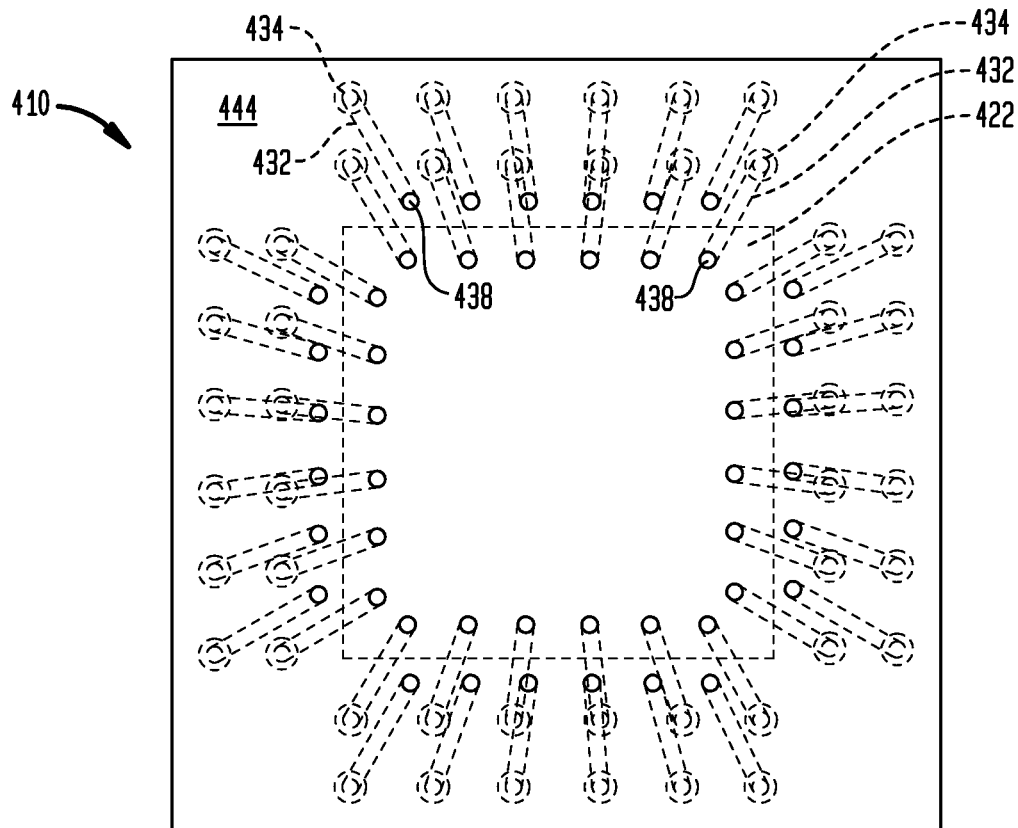
**FIG. 17B**



**FIG. 17C**



**FIG. 18**



**FIG. 19**

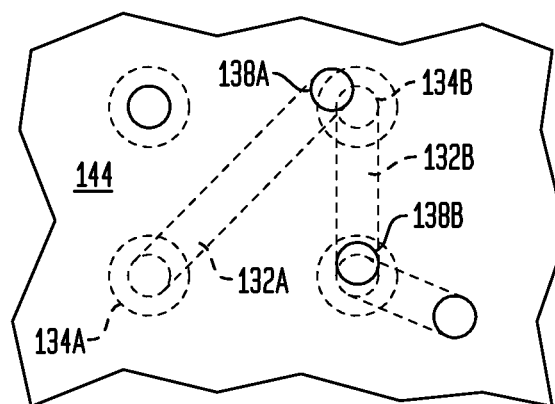


FIG. 20

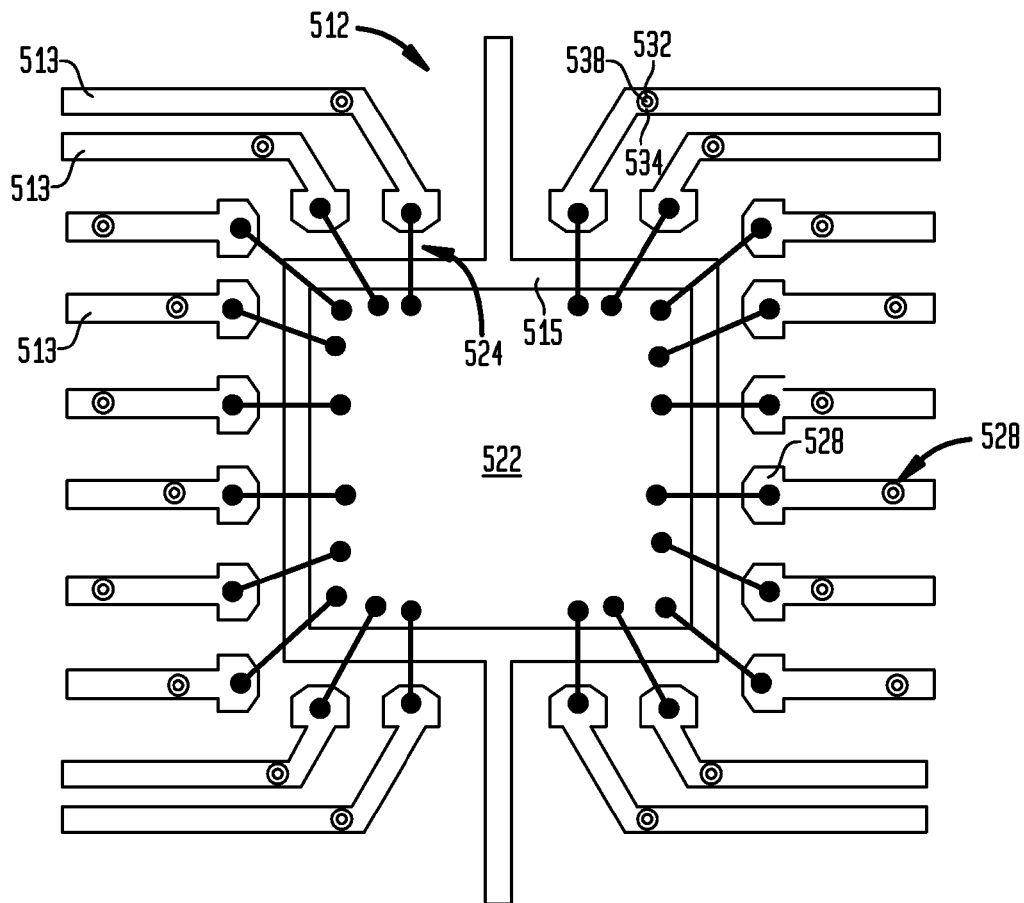


FIG. 21

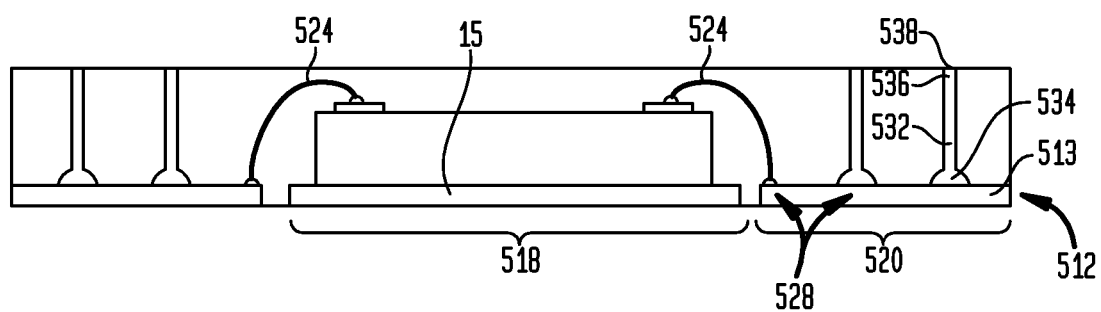




FIG. 22

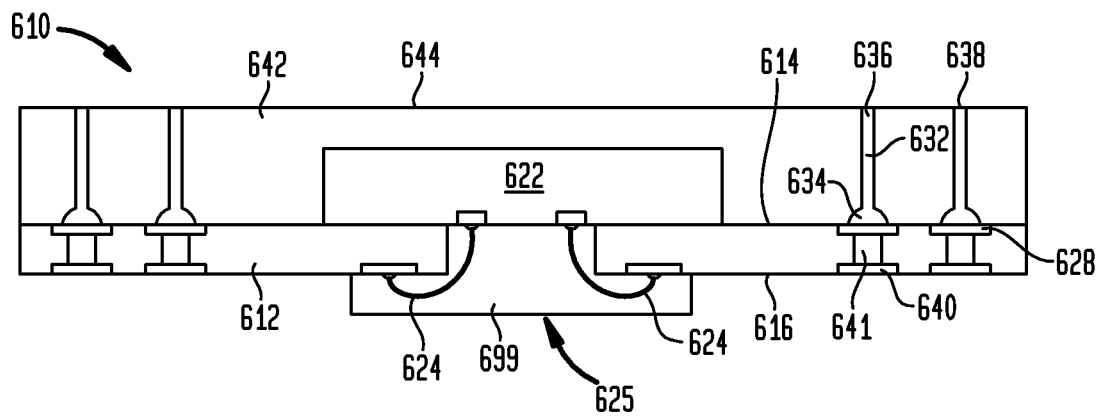


FIG. 23

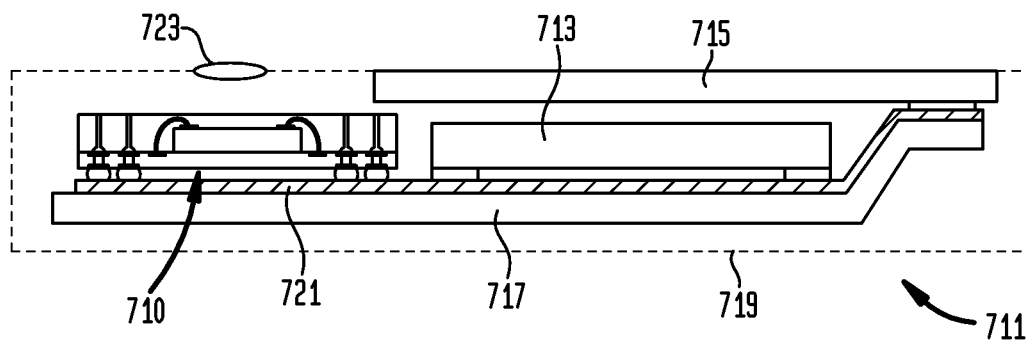


FIG. 24

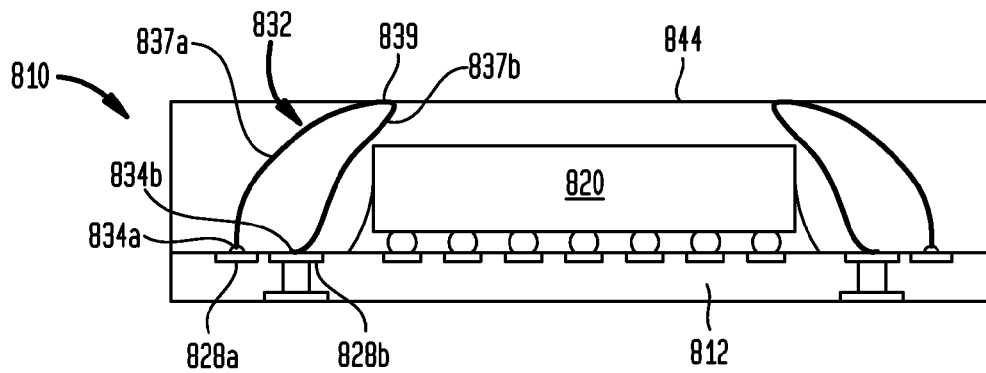


FIG. 25

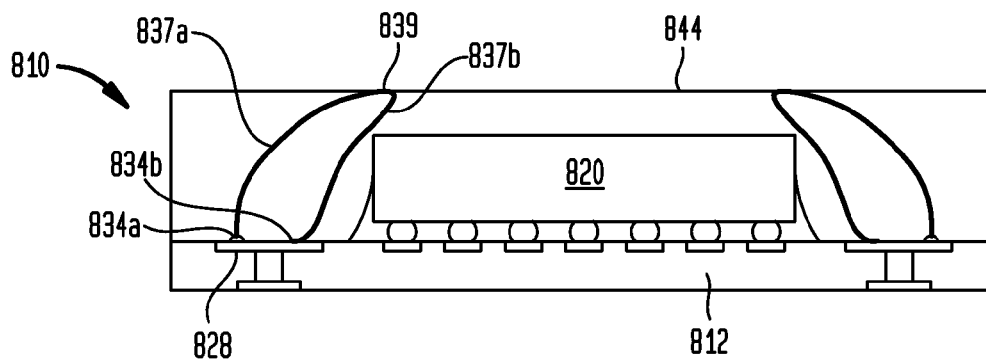
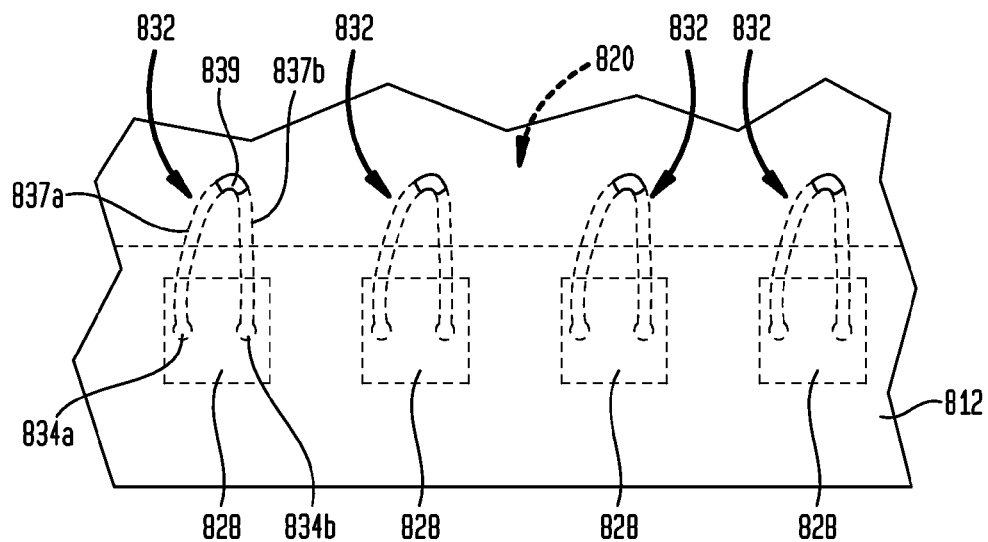
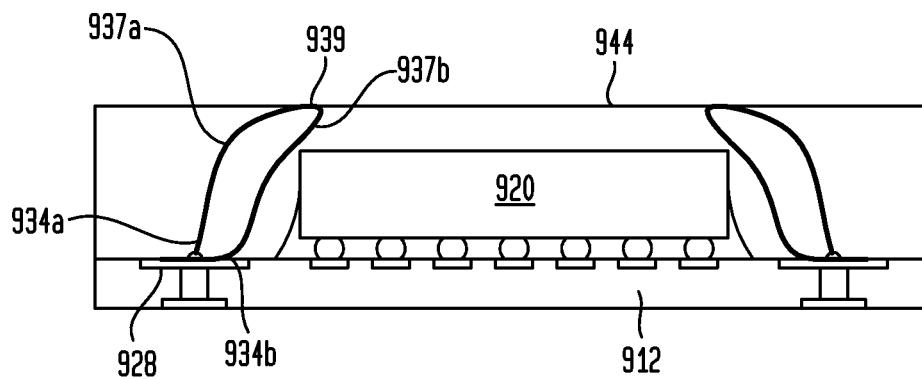


FIG. 26



**FIG. 27**



**FIG. 28**

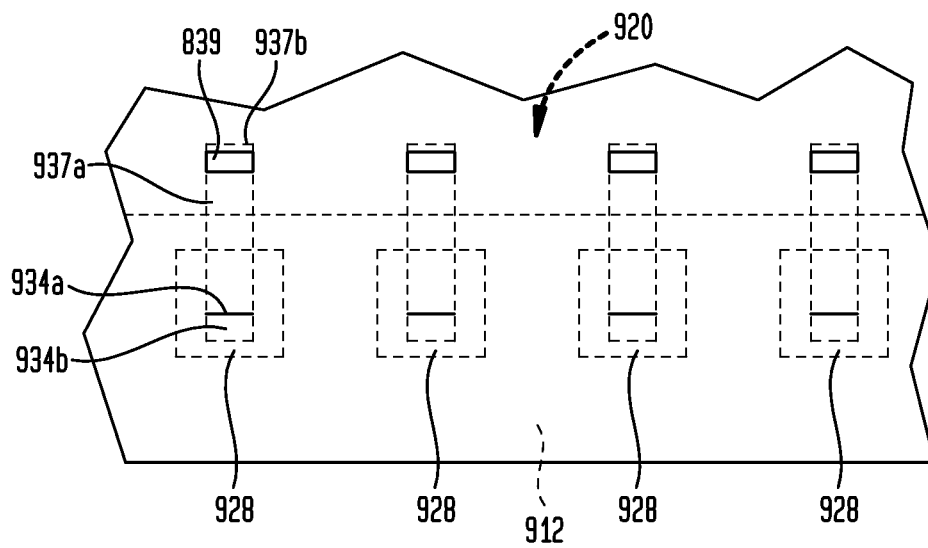


FIG. 29

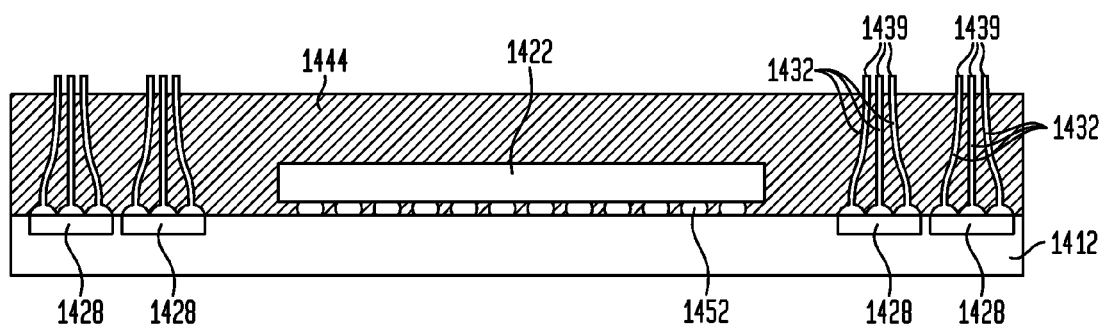
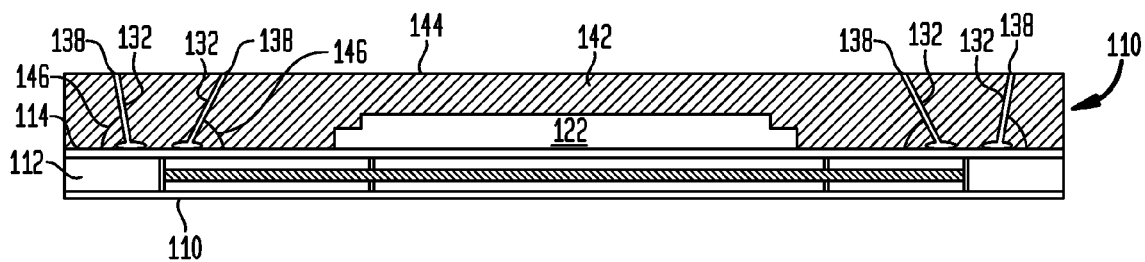
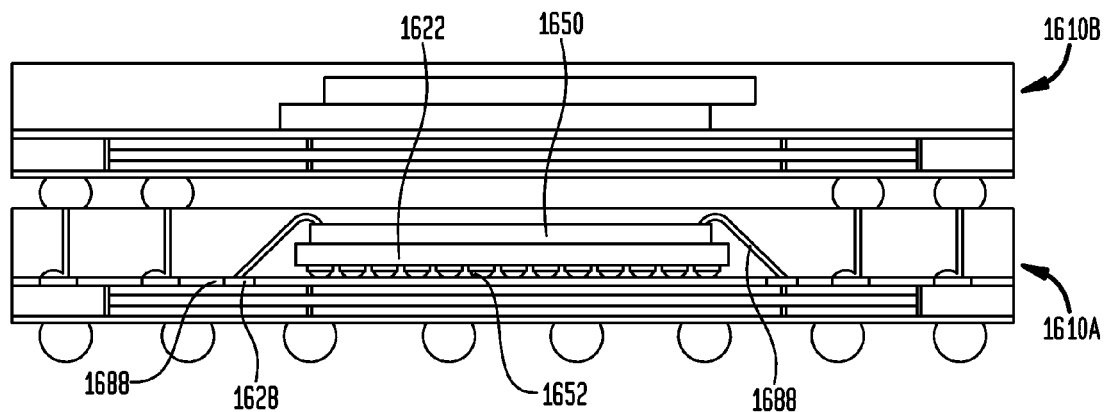


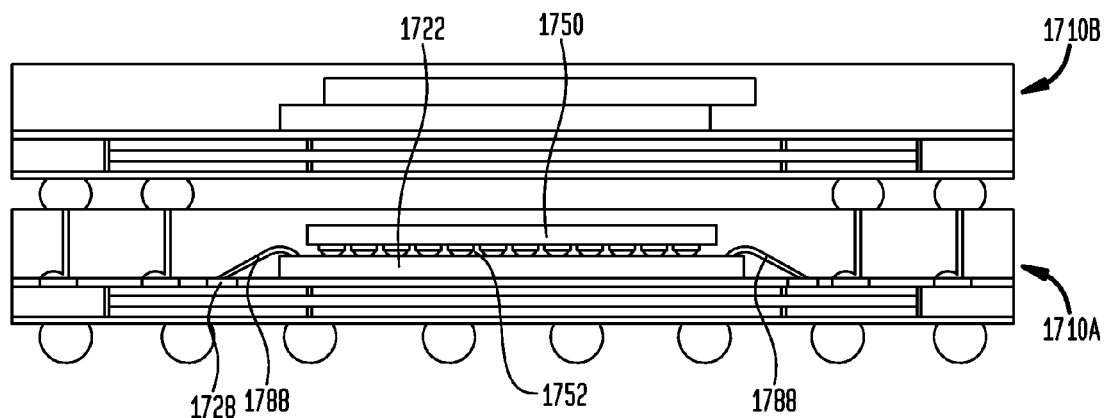
FIG. 30



**FIG. 31A**



**FIG. 31B**



**FIG. 31C**

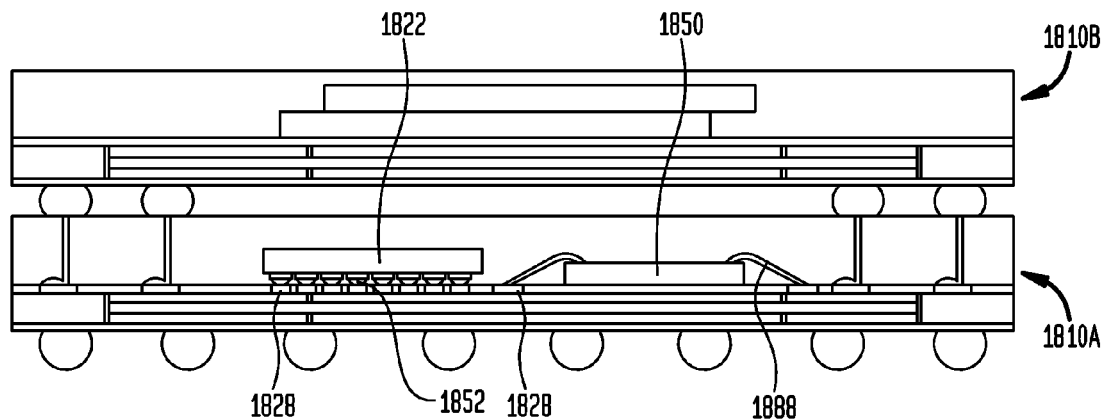


FIG. 32A

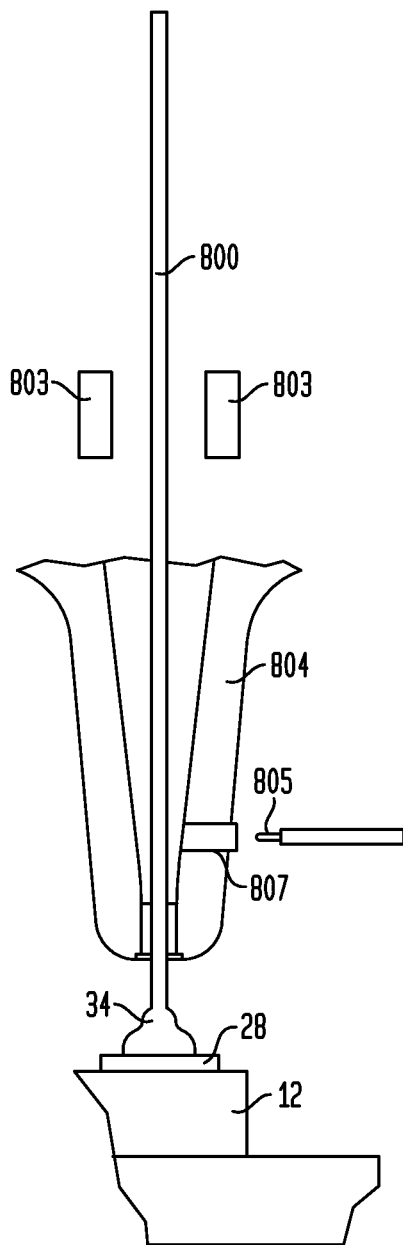
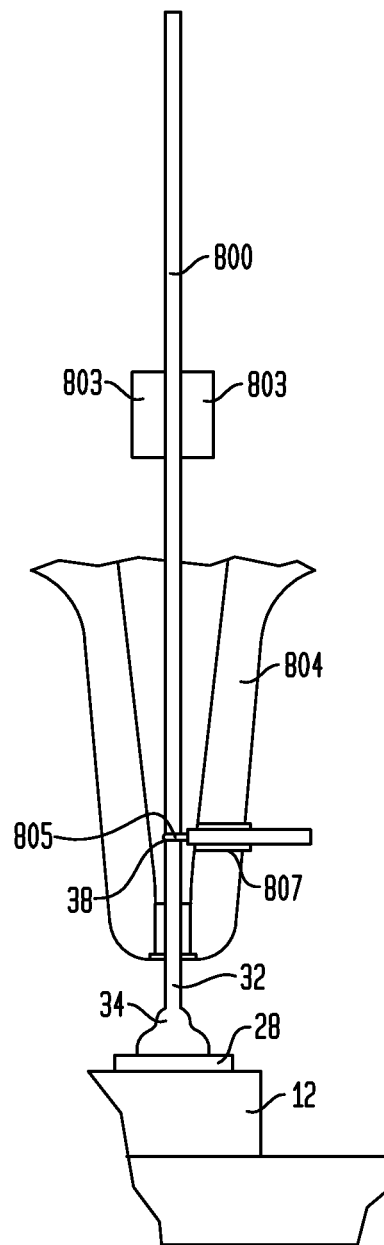


FIG. 32B



**FIG. 33**

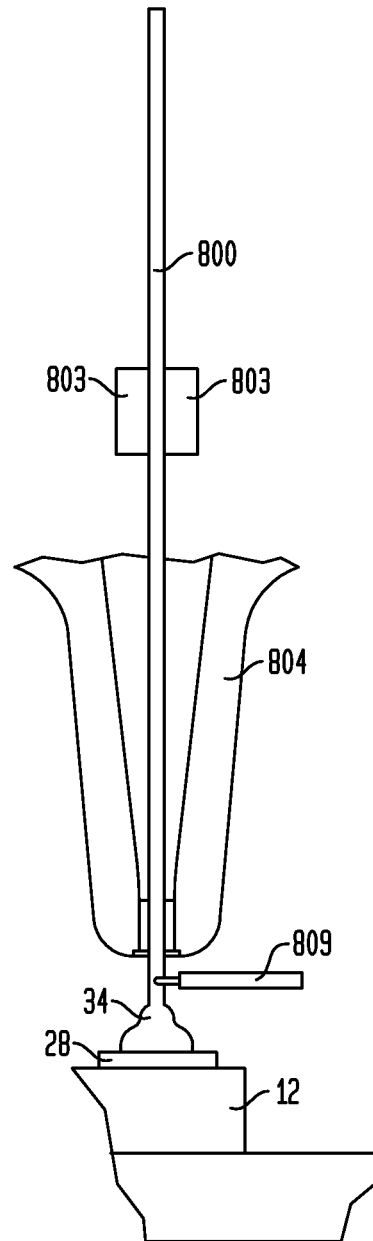




FIG. 34A

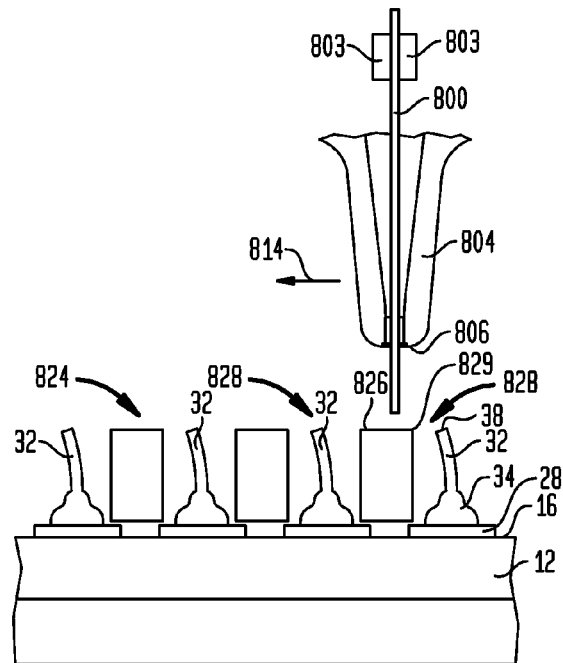


FIG. 34B

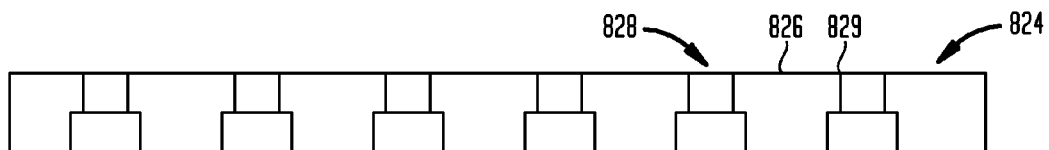
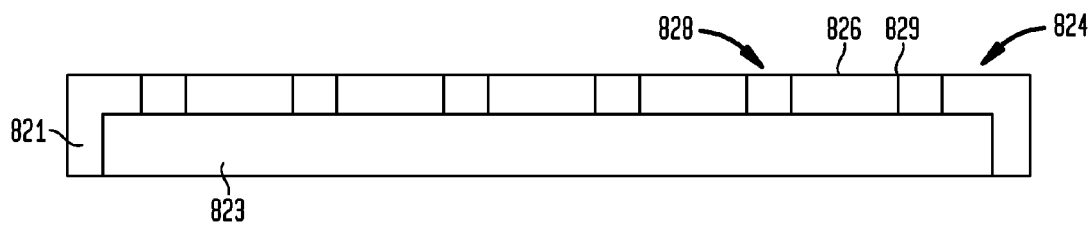


FIG. 34C



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# METHOD FOR PACKAGE-ON-PACKAGE ASSEMBLY WITH WIRE BONDS TO ENCAPSULATION SURFACE

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a national phase entry under 35 U.S.C. §371 of International Application No. PCT/US2013/026126 filed Feb. 14, 2013, which is a continuation of U.S. patent application Ser. No. 13/752,485 filed Jan. 29, 2013, now U.S. Pat. No. 8,772,152, which is a continuation of U.S. patent application Ser. No. 13/405,125 filed Feb. 24, 2012, now U.S. Pat. No. 8,372,741, all of which are hereby incorporated herein by reference.

## BACKGROUND OF THE INVENTION

Embodiments of the invention herein relate to various structures and ways of making microelectronic packages which can be used in package-on-package assemblies, and more particularly, to such structures which incorporate wire bonds for as part of the package-on-package connections.

Microelectronic devices such as semiconductor chips typically require many input and output connections to other electronic components. The input and output contacts of a semiconductor chip or other comparable device are generally disposed in grid-like patterns that substantially cover a surface of the device (commonly referred to as an “area array”) or in elongated rows which may extend parallel to and adjacent each edge of the device’s front surface, or in the center of the front surface. Typically, devices such as chips must be physically mounted on a substrate such as a printed circuit board, and the contacts of the device must be electrically connected to electrically conductive features of the circuit board.

Semiconductor chips are commonly provided in packages that facilitate handling of the chip during manufacture and during mounting of the chip on an external substrate such as a circuit board or other circuit panel. For example, many semiconductor chips are provided in packages suitable for surface mounting. Numerous packages of this general type have been proposed for various applications. Most commonly, such packages include a dielectric element, commonly referred to as a “chip carrier” with terminals formed as plated or etched metallic structures on the dielectric. These terminals typically are connected to the contacts of the chip itself by features such as thin traces extending along the chip carrier itself and by fine leads or wires extending between the contacts of the chip and the terminals or traces. In a surface mounting operation, the package is placed onto a circuit board so that each terminal on the package is aligned with a corresponding contact pad on the circuit board. Solder or other bonding material is provided between the terminals and the contact pads. The package can be permanently bonded in place by heating the assembly so as to melt or “reflow” the solder or otherwise activate the bonding material.

Many packages include solder masses in the form of solder balls, typically about 0.1 mm and about 0.8 mm (5 and 30 mils) in diameter, attached to the terminals of the package. A package having an array of solder balls projecting from its bottom surface is commonly referred to as a ball grid array or “BGA” package. Other packages, referred to as land grid array or “LGA” packages are secured to the substrate by thin layers or lands formed from solder. Packages of this type can be quite compact. Certain packages, commonly referred to as “chip scale packages,” occupy an area of the circuit board

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equal to, or only slightly larger than, the area of the device incorporated in the package. This is advantageous in that it reduces the overall size of the assembly and permits the use of short interconnections between various devices on the substrate, which in turn limits signal propagation time between devices and thus facilitates operation of the assembly at high speeds.

Packaged semiconductor chips are often provided in “stacked” arrangements, wherein one package is provided, for example, on a circuit board, and another package is mounted on top of the first package. These arrangements can allow a number of different chips to be mounted within a single footprint on a circuit board and can further facilitate high-speed operation by providing a short interconnection between packages. Often, this interconnect distance is only slightly larger than the thickness of the chip itself. For interconnection to be achieved within a stack of chip packages, it is necessary to provide structures for mechanical and electrical connection on both sides of each package (except for the topmost package). This has been done, for example, by providing contact pads or lands on both sides of the substrate to which the chip is mounted, the pads being connected through the substrate by conductive vias or the like. Solder balls or the like have been used to bridge the gap between the contacts on the top of a lower substrate to the contacts on the bottom of the next higher substrate. The solder balls must be higher than the height of the chip in order to connect the contacts. Examples of stacked chip arrangements and interconnect structures are provided in U.S. Patent App. Pub. No. 2010/0232129 (“the ‘129 Publication”), the disclosure of which is incorporated by reference herein in its entirety.

Microcontact elements in the form of elongated posts or pins may be used to connect microelectronic packages to circuit boards and for other connections in microelectronic packaging. In some instances, microcontacts have been formed by etching a metallic structure including one or more metallic layers to form the microcontacts. The etching process limits the size of the microcontacts. Conventional etching processes typically cannot form microcontacts with a large ratio of height to maximum width, referred to herein as “aspect ratio”. It has been difficult or impossible to form arrays of microcontacts with appreciable height and very small pitch or spacing between adjacent microcontacts. Moreover, the configurations of the microcontacts formed by conventional etching processes are limited.

Despite all of the above-described advances in the art, still further improvements in making and testing microelectronic packages would be desirable.

## BRIEF SUMMARY OF THE INVENTION

A microelectronic assembly may include a substrate having a first and second opposed surfaces. A microelectronic element can overlie the first surface and first electrically conductive elements can be exposed at at least one of the first surface or second surfaces. Some of the first conductive elements may be electrically connected to the microelectronic element. Wire bonds have bases joined to the conductive elements and end surfaces remote from the substrate and the bases. Each wire bond can define an edge surface extending between the base and the end surface. An encapsulation layer can extend from the first surface and fill spaces between the wire bonds, such that the wire bonds can be separated by the encapsulation layer. Unencapsulated portions of the wire bonds may be defined by at least portions of the end surfaces of the wire bonds that are uncovered by the encapsulation layer.

Various package structures are disclosed herein which incorporate wire bonds functioning as vertical connections extending upwardly from conductive elements, e.g., conductive pads on a substrate. Such wire bonds can be used in making package on package electrical connections with a microelectronic package overlying a surface of a dielectric encapsulation. In addition, various embodiments of methods are disclosed herein for making a microelectronic package or a microelectronic assembly.

Thus, a method of making a microelectronic package according to an aspect of the invention can include a) feeding a metal wire segment having a predetermined length out of a capillary of a bonding tool; b) using the bonding tool to bond a portion of the metal wire to a conductive element exposed at a first surface of a substrate, thereby forming a base of a wire bond on the conductive element; c) clamping a portion of the wire within the bonding tool; d) cutting the metal wire at a location between the clamped portion and the base portion to at least partially define an end surface of the wire bond, an edge surface of the wire bond being defined between the base and the end surface; e) repeating steps (a) through (d) to form a plurality of wire bonds to a plurality of the conductive elements of the substrate; and e) then forming a dielectric encapsulation layer overlying the surface of the substrate, wherein the encapsulation layer is formed so as to at least partially cover the surface of the substrate and portions of the wire bonds, such that unencapsulated portions of the wire bonds are defined by a portion of at least one of an end surface or of an edge surface thereof that is uncovered by the encapsulation layer.

Thus, in accordance with an aspect of the invention, a metal wire segment having a predetermined length can be fed out of a capillary of a bonding tool. The bonding tool can be used to bond a portion of the metal wire to a conductive element exposed at a first surface of a substrate. Such bonding can form a base of the wire bond on the conductive element. A portion of the wire can be clamped after forming the bond with the conductive element. The portion of the wire clamped can be within the bonding tool. The metal wire can be cut at a location between the clamped portion and the base portion, and cutting the wire may at least partially define an end surface of the wire bond. An edge surface of the wire bond can be defined between the base and the end surface. The foregoing can be repeated to form a plurality of wire bonds to a plurality of the conductive elements of the substrate. Then, a dielectric encapsulation layer can be formed overlying the surface of the substrate. The encapsulation layer can be formed so as to at least partially cover the surface of the substrate and portions of the wire bonds. Unencapsulated portions of the wire bonds can be defined by a portion of at least one of an end surface or of an edge surface thereof that is uncovered by the encapsulation layer.

In one example, the metal wire can be cut only partially therethrough. The bonding tool can be moved away from the surface of the substrate while the portion of the wire remains clamped. In such process, the wire can be caused to break at the location of the cut. An end surface can be formed by the cut and the break.

In one example, the cut can be made completely through the wire segment in a direction substantially perpendicular to the edge surface of the wire bond. An end surface of the wire bond can be formed by the cut.

In one example, at least one microelectronic element can overlie the first surface of the substrate. The substrate can have a first region and a second region and the microelectronic element can be located within the first region, e.g., as overlying the first region. The conductive elements can be

located within the second region, e.g., as conductive elements exposed at the first surface therein. The conductive elements can be electrically connected to the at least one microelectronic element. The dielectric encapsulation layer can be formed overlying the first surface of the substrate in at least the second region thereof, but may overlie at least a portion of the first surface in the first region as well as the second region.

In one example, the package can be configured such that a first wire bond of the wire bonds is adapted for carrying a first signal electric potential and a second wire bond of the wire bonds is adapted for simultaneously carrying a second signal electric potential different from the first signal electric potential.

In one example, the metal wire segment can be cut using a laser mounted on the bonding tool. In such example, the capillary of the bonding tool can define a face thereof through which the wire segment is fed. The laser can be mounted on or with the bonding tool such that a cutting beam can be directed to a location of the wire segment positioned between the face of the bonding tool and the base of the wire bond.

In one example, the bonding tool can include a capillary defining a face thereof through which the wire segment is fed. The capillary may include an opening in a side wall thereof, and the laser can be mounted on or with the bonding such that a cutting beam can pass through the opening to a location of the wire segment positioned within the capillary.

In one example, the laser can be one of: CO<sub>2</sub>, Nd:YAG, or a Cu vapor laser.

In one example, the metal wire can be cut using a cutting edge that extends within the capillary. In one example, the cutting edge can extend in a direction toward a wall of the capillary opposite the wire segment. In one example, the metal wire can be cut using the cutting edge as a first cutting edge, and in combination with a second cutting edge that extends within the capillary. The second cutting edge may be positioned in opposition with the first cutting edge.

In one example, the capillary may define a face through which the wire segment can be fed. The metal wire can be cut using a cutting instrument having first and second opposing cutting edges. The cutting instrument can be mounted on or with the bonding tool in such way that the wire can be cut at a location positioned between the face of the bonding tool and the base of the wire bond.

One example of the method may include positioning a stencil over the substrate. The stencil can have a plurality of openings therein that overlie and expose at least portions of the conductive elements. The openings can define respective edges positioned at a first height over the substrate. The wire segment can be cut by lateral movement of the wire against the edge of the stencil opening.

A method of making a microelectronic package according to an aspect of the invention can include: positioning a stencil over an in-process unit including a substrate having a first surface and a second surface remote therefrom. A microelectronic element can be mounted to the first surface of the substrate. A plurality of conductive elements can be exposed at the first surface. In an example, at least some of the conductive elements can be electrically connected to the microelectronic element. The stencil can have a plurality of openings therein that overlie and expose at least portion of the conductive elements. The openings may define respective edges which are positioned at a first height over the substrate.

In accordance with such aspect, the method can include forming a wire bond by a process including feeding a metal wire out of a capillary of a bonding tool such that a predetermined length extends beyond the face of the capillary and defines a metal wire segment. A portion of the wire segment

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can be joined to a conductive element of the plurality of conductive elements to form a base of the wire bond. At least a portion of the metal wire segment can be sheared from another portion of the wire connected thereto by lateral movement of the wire against the edge of the stencil opening to separate the wire bond from a remaining portion of the wire. The shearing of the metal wire can define an end surface of the wire bond, the wire bond having an edge surface extending between the base and the end surface. The feeding out of the metal wire, bonding, and shearing thereof as described above can be repeated a plurality of times using one or more openings of the stencil to form a plurality of wire bonds on a plurality of the conductive elements.

In an example of such method, a dielectric encapsulation layer can be formed on the in-process unit, wherein the encapsulation layer is formed so as to at least partially cover the first surface and portions of the wire bonds. Unencapsulated portions of the wire bonds can be defined by a portion of at least one of the end surface or of the edge surface thereof which is uncovered by the encapsulation layer.

In an example of such method, a portion of the metal wire which extends beyond a face of the capillary and which remains after the shearing of the metal wire can be of a length sufficient to form at least a base of a subsequent wire bond.

In an example of the method, the stencil can define a thickness in a direction of an axis extending of one of the holes, e.g., in a vertical direction away from a surface of the substrate. Some or all of the holes can have a consistent or constant diameter through the thickness of the stencil.

In an example of the method, the stencil can define a thickness in a direction of an axis of one of the holes or openings, e.g., in a vertical direction away from a surface of the substrate. Some or all of the holes or openings in the stencil can be tapered from a first width or smaller diameter at an exposed edge within the opening to a second larger width or greater diameter at another location within the hole or opening and closer to the substrate.

In one example, the stencil may include an edge member having a first thickness in a direction of thickness of the substrate extending along one or more edges of the substrate. The first thickness can define a first height. A central portion may include the holes or openings and can be bounded by the edge member. The central portion can have an outer surface facing away from the substrate. The outer surface can be disposed at the first height. The central portion can have a thickness which is less than the first thickness.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a microelectronic package according to an embodiment of the present invention;

FIG. 2 shows a top elevation view of the microelectronic package of FIG. 1;

FIG. 3 shows a microelectronic package according to an alternative embodiment of the present invention;

FIG. 4 shows a microelectronic package according to an alternative embodiment of the present invention;

FIG. 5 shows a microelectronic package according to an alternative embodiment of the present invention;

FIG. 6 shows a stacked microelectronic assembly including a microelectronic package according to an embodiment of the present invention;

FIG. 7 shows a microelectronic package according to an alternative embodiment of the present invention;

FIGS. 8A-8E show a detail view of a portion of a microelectronic package according to various embodiments of the present invention;

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FIG. 9 shows a detail view of a portion of a microelectronic package according to an alternative embodiment of the present invention;

FIGS. 10A-10D show a detail view of a portion of a microelectronic package according to various embodiments of the present invention;

FIGS. 11-14 show a microelectronic package during various steps of fabrication thereof according to an embodiment of the present invention;

FIG. 15 shows a microelectronic package during a fabrication step according to an alternative embodiment of the present invention;

FIGS. 16A-16C show a detail view of a portion of a microelectronic package during various steps of fabrication thereof according to an embodiment of the present invention;

FIGS. 17A-17C show a detail view of a portion of a microelectronic package during various steps of fabrication thereof according to an alternative embodiment of the present invention;

FIG. 18 shows a top elevation view of a microelectronic package according to an alternative embodiment of the present invention;

FIG. 19 shows a top elevation view of a portion of a microelectronic package according to an alternative embodiment of the present invention;

FIG. 20 shows a top view of a microelectronic package according to a further alternative embodiment of the present invention;

FIG. 21 shows a front elevation view of the microelectronic package of FIG. 20;

FIG. 22 shows a front elevation view of a microelectronic package according to a further alternative embodiment of the present invention;

FIG. 23 shows a system according to a further embodiment of the present invention;

FIG. 24 shows a front elevation view of a microelectronic package according to a further alternative embodiment of the present invention;

FIG. 25 shows a front elevation view of a microelectronic package according to a further alternative embodiment of the present invention;

FIG. 26 shows a top view of a microelectronic package according to a variation of the embodiment of FIG. 25;

FIG. 27 shows a front elevation view of a microelectronic package according to a further alternative embodiment of the present invention;

FIG. 28 shows a top view of a microelectronic package according to a variation of the embodiment of FIG. 27;

FIG. 29 is a sectional view of a microelectronic package according to a further embodiment;

FIG. 30 shows a sectional view of a microelectronic package according to another embodiment;

FIGS. 31A-C are sectional views showing examples of embodiments of microelectronic packages according to further embodiments;

FIGS. 32A and 32B show a portion of a machine that can be used in forming various wire bond vias in various stages of a method according to another embodiment of the present disclosure;

FIG. 33 shows a portion of a machine that can be used in forming various wire bond vias according to another embodiment of the present disclosure; and

FIGS. 34A-C show various forms of an instrument that can be used in a method for making wire bonds according to an embodiment of the present disclosure.

## DETAILED DESCRIPTION

Turning now to the figures, where similar numeric references are used to indicate similar features, there is shown in FIG. 1 a microelectronic assembly 10 according to an embodiment of the present invention. The embodiment of FIG. 1 is a microelectronic assembly in the form of a packaged microelectronic element such as a semiconductor chip assembly that is used in computer or other electronic applications.

The microelectronic assembly 10 of FIG. 1 includes a substrate 12 having a first surface 14 and a second surface 16. The substrate 12 typically is in the form of a dielectric element, which is substantially flat. The dielectric element may be sheet-like and may be thin. In particular embodiments, the dielectric element can include one or more layers of organic dielectric material or composite dielectric materials, such as, without limitation: polyimide, polytetrafluoroethylene ("PTFE"), epoxy, epoxy-glass, FR-4, BT resin, thermoplastic, or thermoset plastic materials. The first surface 14 and second surface 16 are preferably substantially parallel to each other and are spaced apart at a distance perpendicular to the surfaces 14, 16 defining the thickness of the substrate 12. The thickness of substrate 12 is preferably within a range of generally acceptable thicknesses for the present application. In an embodiment, the distance between the first surface 14 and the second surface 16 is between about 25 and 500  $\mu\text{m}$ . For purposes of this discussion, the first surface 14 may be described as being positioned opposite or remote from second surface 16. Such a description, as well as any other description of the relative position of elements used herein that refers to a vertical or horizontal position of such elements is made for illustrative purposes only to correspond with the position of the elements within the Figures, and is not limiting.

In a preferred embodiment, substrate 12 is considered as divided into a first region 18 and a second region 20. The first region 18 lies within the second region 20 and includes a central portion of the substrate 12 and extends outwardly therefrom. The second region 20 substantially surrounds the first region 18 and extends outwardly therefrom to the outer edges of the substrate 12. In this embodiment, no specific characteristic of the substrate itself physically divides the two regions; however, the regions are demarked for purposes of discussion herein with respect to treatments or features applied thereto or contained therein.

A microelectronic element 22 can be mounted to first surface 14 of substrate 12 within first region 18. Microelectronic element 22 can be a semiconductor chip or another comparable device. In the embodiment of FIG. 1, microelectronic element 22 is mounted to first surface 14 in what is known as a conventional or "face-up" fashion. In such an embodiment, wire leads 24 can be used to electrically connect microelectronic element 22 to some of a plurality of conductive elements 28 exposed at first surface 14. Wire leads 24 can also be joined to traces (not shown) or other conductive features within substrate 12 that are, in turn, connected to conductive elements 28.

Conductive elements 28 include respective "contacts" or pads 30 that are exposed at the first surface 14 of substrate 12. As used in the present description, when an electrically conductive element is described as being "exposed at" the surface of another element having dielectric structure, it indicates that the electrically conductive structure is available for contact with a theoretical point moving in a direction perpendicular to the surface of the dielectric structure toward the surface of the dielectric structure from outside the dielectric structure. Thus, a terminal or other conductive structure that is exposed

at a surface of a dielectric structure may project from such surface; may be flush with such surface; or may be recessed relative to such surface and exposed through a hole or depression in the dielectric. The conductive elements 28 can be flat, thin elements in which pad 30 is exposed at first surface 14 of substrate 12. In one embodiment, conductive elements 28 can be substantially circular and can be interconnected between each other or to microelectronic element 22 by traces (not shown). Conductive elements 28 can be formed at least within second region 20 of substrate 12. Additionally, in certain embodiments, conductive elements 28 can also be formed within first region 18. Such an arrangement is particularly useful when mounting microelectronic element 122 (FIG. 3) to substrate 112 in what is known as a "flip-chip" configuration, where contacts on the microelectronic element 122 can be connected to conductive elements 128 within first region 118 by solder bumps 126 or the like that are positioned beneath microelectronic element 122. In another configuration as shown in FIG. 22, microelectronic element 622 is mounted face-down on substrate 612 and electrically connected to a conductive feature on the chip by wire leads 624 that extend over an outwardly-facing surface, such as surface 616, of substrate 612. In the embodiment shown, wire leads 625 pass through an opening 625 in substrate 612 and can be encapsulated by an overmold 699.

In an embodiment, conductive elements 28 are formed from a solid metal material such as copper, gold, nickel, or other materials that are acceptable for such an application, including various alloys including one or more of copper, gold, nickel or combinations thereof.

At least some of conductive elements 28 can be interconnected to corresponding second conductive elements 40, such as conductive pads, exposed at second surface 16 of substrate 12. Such an interconnection can be completed using vias 41 formed in substrate 12 that can be lined or filled with conductive metal that can be of the same material as conductive elements 28 and 40. Optionally, conductive elements 40 can be further interconnected by traces on substrate 12.

Microelectronic assembly 10 further includes a plurality of wire bonds 32 joined to at least some of the conductive elements 28, such as on the pads 30 thereof. Wire bonds 32 are joined at a base 34 thereof to the conductive elements 28 and can extend to a free end 36 remote from the respective bases 34 and from substrate 12. The ends 36 of wire bonds 32 are characterized as being free in that they are not electrically connected or otherwise joined to microelectronic element 22 or any other conductive features within microelectronic assembly 10 that are, in turn, connected to microelectronic element 22. In other words, free ends 36 are available for electronic connection, either directly or indirectly as through a solder ball or other features discussed herein, to a conductive feature external to assembly 10. The fact that ends 36 held in a predetermined position by, for example, encapsulant layer 42 or otherwise joined or electrically connected to another conductive feature does not mean that they are not "free" as described herein, so long as any such feature is not electrically connected to microelectronic element 22. Conversely, base 34 is not free as it is either directly or indirectly electrically connected to microelectronic element 22, as described herein. As shown in FIG. 1, base 34 can be substantially rounded in shape, extending outward from an edge surface 37 of wire bond 32 defined between base 34 and end 36. The particular size and shape of base 34 can vary according to the type of material used to form wire bond 32, the desired strength of the connection between wire bond 32 and conductive element 28, or the particular process used to form wire bond 32. Exemplary methods for making wire bonds 28

are described in U.S. Pat. No. 7,391,121 to Otremba and in U.S. Pat. App. Pub. No. 2005/0095835 (describing a wedge-bonding procedure that can be considered a form of wire bonding) the disclosures of which are both incorporated herein by reference in their entireties. Alternative embodiments are possible where wire bonds 32 are additionally or alternatively joined to conductive elements 40 exposed on second surface 16 of substrate 12, extending away therefrom.

Wire bond 32 can be made from a conductive material such as copper, gold, nickel, solder, aluminum or the like. Additionally, wire bonds 32 can be made from combinations of materials, such as from a core of a conductive material, such as copper or aluminum, for example, with a coating applied over the core. The coating can be of a second conductive material, such as aluminum, nickel or the like. Alternatively, the coating can be of an insulating material, such as an insulating jacket. In an embodiment, the wire used to form wire bonds 32 can have a thickness, i.e., in a dimension transverse to the wire's length, of between about 15  $\mu\text{m}$  and 150  $\mu\text{m}$ . In other embodiments, including those in which wedge bonding is used, wire bonds 32 can have a thickness of up to about 500  $\mu\text{m}$ . In general, a wire bond is formed on a conductive element, such as conductive element 28, a pad, trace or the like, using specialized equipment that is known in the art. A leading end of a wire segment is heated and pressed against the receiving surface to which the wire segment bonds, typically forming a ball or ball-like base 34 joined to the surface of the conductive element 28. The desired length of the wire segment to form the wire bond is drawn out of the bonding tool, which can then cut the wire bond at the desired length. Wedge bonding, which can be used to form wire bonds of aluminum, for example, is a process in which the heated portion of the wire is dragged across the receiving surface to form a wedge that lies generally parallel to the surface. The wedge-bonded wire bond can then be bent upward, if necessary, and extended to the desired length or position before cutting. In a particular embodiment, the wire used to form a wire bond can be cylindrical in cross-section. Otherwise, the wire fed from the tool to form a wire bond or wedge-bonded wire bond may have a polygonal cross-section such as rectangular or trapezoidal, for example.

The free end 36 of wire bond 32 has an end surface 38. End surface 38 can form at least a part of a contact in an array formed by respective end surfaces 38 of a plurality of wire bonds 32. FIG. 2 shows an exemplary pattern for such an array of contacts formed by end surfaces 38. Such an array can be formed in an area array configuration, variations of which could be implemented using the structures described herein. Such an array can be used to electrically and mechanically connect the microelectronic assembly 10 to another microelectronic structure, such as to a printed circuit board ("PCB"), or to other packaged microelectronic elements, an example of which is shown in FIG. 6. In such a stacked arrangement, wire bonds 32 and conductive elements 28 and 40 can carry multiple electronic signals therethrough, each having a different signal potential to allow for different signals to be processed by different microelectronic elements in a single stack. Solder masses 52 can be used to interconnect the microelectronic assemblies in such a stack, such as by electronically and mechanically attaching end surfaces 38 to conductive elements 40.

Microelectronic assembly 10 further includes an encapsulation layer 42 formed from a dielectric material. In the embodiment of FIG. 1, encapsulation layer 42 is formed over the portions of first surface 14 of substrate 12 that are not otherwise covered by or occupied by microelectronic element 22, or conductive elements 28. Similarly, encapsulation layer

42 is formed over the portions of conductive elements 28, including pad 30 thereof, that are not otherwise covered by wire bonds 32. Encapsulation layer 42 can also substantially cover microelectronic element 22, wire bonds 32, including the bases 34 and at least a portion of edge surfaces 37 thereof. A portion of wire bonds 32 can remain uncovered by encapsulation layer 42, which can also be referred to as unencapsulated, thereby making the wire bond available for electrical connection to a feature or element located outside of encapsulation layer 42. In an embodiment, end surfaces 38 of wire bonds 32 remain uncovered by encapsulation layer 42 within major surface 44 of encapsulation layer 42. Other embodiments are possible in which a portion of edge surface 37 is uncovered by encapsulation layer 42 in addition to or as an alternative to having end surface 38 remain uncovered by encapsulation layer 42. In other words, encapsulation layer 42 can cover all of microelectronic assembly 10 from first surface 14 and above, with the exception of a portion of wire bonds 36, such as end surfaces 38, edge surfaces 37 or combinations of the two. In the embodiments shown in the Figures, a surface, such as major surface 44 of encapsulation layer 42 can be spaced apart from first surface 14 of substrate 12 at a distance great enough to cover microelectronic element 22. Accordingly, embodiments of microelectronic assembly 10 in which ends 38 of wire bonds 32 are flush with surface 44, will include wire bonds 32 that are taller than the microelectronic element 22, and any underlying solder bumps for flip chip connection. Other configurations for encapsulation layer 42, however, are possible. For example, the encapsulation layer can have multiple surfaces with varying heights. In such a configuration, the surface 44 within which ends 38 are positioned can be higher or lower than an upwardly facing surface under which microelectronic element 22 is located.

Encapsulation layer 42 serves to protect the other elements within microelectronic assembly 10, particularly wire bonds 32. This allows for a more robust structure that is less likely to be damaged by testing thereof or during transportation or assembly to other microelectronic structures. Encapsulation layer 42 can be formed from a dielectric material with insulating properties such as that described in U.S. Patent App. Pub. No. 2010/0232129, which is incorporated by reference herein in its entirety.

FIG. 3 shows an embodiment of microelectronic assembly 110 having wire bonds 132 with ends 136 that are not positioned directly above the respective bases 34 thereof. That is, considering first surface 114 of substrate 112 as extending in two lateral directions, so as to substantially define a plane, end 136 or at least one of the wire bonds 132 is displaced in at least one of these lateral directions from a corresponding lateral position of base 134. As shown in FIG. 3, wire bonds 132 can be substantially straight along the longitudinal axis thereof, as in the embodiment of FIG. 1, with the longitudinal axis being angled at an angle 146 with respect to first surface 114 of substrate 112. Although the cross-sectional view of FIG. 3 only shows the angle 146 through a first plane perpendicular to first surface 114, wire bond 132 can also be angled with respect to first surface 114 in another plane perpendicular to both that first plane and to first surface 114. Such an angle can be substantially equal to or different than angle 146. That is the displacement of end 136 relative to base 134 can be in two lateral directions and can be by the same or a different distance in each of those directions.

In an embodiment, various ones of wire bonds 132 can be displaced in different directions and by different amounts throughout the assembly 110. Such an arrangement allows for assembly 110 to have an array that is configured differently on

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the level of surface **144** compared to on the level of substrate **12**. For example, an array can cover a smaller overall area or have a smaller pitch on surface **144** than at the first surface **114** level compared to that at first surface **114** of substrate **112**. Further, some wire bonds **132** can have ends **136** that are positioned above microelectronic element **122** to accommodate a stacked arrangement of packaged microelectronic elements of different sizes. In another example, shown in FIG. **19**, wire bonds **132** can be configured such that the end surface **138A** of one wire bond **132A** is positioned substantially above the base **134B** of another wire bond **132B**, the end surface **138B** of that wire bond **132B** being positioned elsewhere. Such an arrangement can be referred to as changing the relative position of a contact end surface **138** within an array of contacts, compared to the position of a corresponding contact array on second surface **116**. Within such an array, the relative positions of the contact end surfaces can be changed or varied, as desired, depending on the microelectronic assembly's application or other requirements.

In a further example shown in FIG. **30**, the wire bonds **132** can be arranged such that the bases **134** are arranged in a first pattern having a pitch thereof. The wire bonds **132** can be configured such that the unencapsulated portions thereof **139**, including end surfaces **138** can be disposed in a pattern at positions at a major surface **144** of the encapsulation layer **142** which have a minimum pitch that is greater than a minimum pitch between the respective adjacent bases **134** of the wire bonds attached to conductive elements **128**. Accordingly, the minimum pitch between adjacent wire bonds at the encapsulation surface **146** can be greater than the corresponding minimum pitch between the conductive elements **128** of the substrate to which the wire bonds are attached.

To achieve this, the wire bonds can be angled, as shown in FIG. **30**, or can be curved as shown, for example in FIG. **4**, such that the end surfaces **138** are displaced in one or more lateral directions from the bases **134**, as discussed above. As further shown in FIG. **30**, the conductive elements **128** and the end surfaces **138** can be arranged in respective rows or columns and the lateral displacement of end surfaces **138** in one row can be greater than in another row. To achieve this, the wire bonds **132** can, for example be at different angles **146A**, **146B** with respect to the surface **116** of the substrate **112**.

FIG. **4** shows a further embodiment of a microelectronic subassembly **210** having wire bonds **232** with ends **236** in displaced lateral positions with respect to bases **234**. In the embodiment of FIG. **4**, the wire bonds **132** achieve this lateral displacement by including a curved portion **248** therein. Curved portion **248** can be formed in an additional step during the wire bond formation process and can occur, for example, while the wire portion is being drawn out to the desired length. This step can be carried out using available wire-bonding equipment, which can include the use of a single machine.

Curved portion **248** can take on a variety of shapes, as needed, to achieve the desired positions of the ends **236** of the wire bonds **232**. For example, curved portions **248** can be formed as S-curves of various shapes, such as that which is shown in FIG. **4** or of a smoother form (such as that which is shown in FIG. **5**). Additionally, curved portion **248** can be positioned closer to base **234** than to end **236** or vice-versa. Curved portion **248** can also be in the form of a spiral or loop, or can be compound including curves in multiple directions or of different shapes or characters.

FIG. **5** shows a further exemplary embodiment of a microelectronic package **310** having a combination of wire bonds **332** having various shapes leading to various relative lateral displacements between bases **334** and ends **336**. Some of wire

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bonds **332A** are substantially straight with ends **336A** positioned above their respective bases **334A**, while other wire bonds **332B** include a subtle curved portion **348B** leading to a somewhat slight relative lateral displacement between end **336B** and base **334B**. Further, some wire bonds **332C** include curved portions **348C** having a sweeping shape that result in ends **336C** that are laterally displaced from the relative bases **334C** at a greater distance than that of ends **334B**. FIG. **5** also shows an exemplary pair of such wire bonds **332Ci** and **332Cii** that have bases **334Ci** and **334Cii** positioned in the same row of a substrate-level array and ends **336Ci** and **336Cii** that are positioned in different rows of a corresponding surface-level array.

A further variation of a wire bond **332D** is shown that is configured to be uncovered by encapsulation layer **342** on a side surface **47** thereof. In the embodiment shown free end **336D** is uncovered, however, a portion of edge surface **337D** can additionally or alternatively be uncovered by encapsulation layer **342**. Such a configuration can be used for grounding of microelectronic assembly **10** by electrical connection to an appropriate feature or for mechanical or electrical connection to other featured disposed laterally to microelectronic assembly **310**. Additionally, FIG. **5** shows an area of encapsulation layer **342** that has been etched away, molded, or otherwise formed to define a recessed surface **345** that is positioned closer to substrate **12** than major surface **342**. One or more wire bonds, such as wire bond **332A** can be uncovered within an area along recessed surface **345**. In the exemplary embodiment shown in FIG. **5**, end surface **338A** and a portion of edge surface **337A** are uncovered by encapsulation layer **342**. Such a configuration can provide a connection, such as by a solder ball or the like, to another conductive element by allowing the solder to wick along edge surface **337A** and join thereto in addition to joining to end surface **338**. Other configurations by which a portion of a wire bond can be uncovered by encapsulation layer **342** along recessed surface **345** are possible, including ones in which the end surfaces are substantially flush with recessed surface **345** or other configurations shown herein with respect to any other surfaces of encapsulation layer **342**. Similarly, other configurations by which a portion of wire bond **332D** is uncovered by encapsulation layer **342** along side surface **347** can be similar to those discussed elsewhere herein with respect to the variations of the major surface of the encapsulation layer.

FIG. **5** further shows a microelectronic assembly **310** having two microelectronic elements **322** and **350** in an exemplary arrangement where microelectronic element **350** is stacked, face-up, on microelectronic element **322**. In this arrangement, leads **324** are used to electrically connect microelectronic element **322** to conductive features on substrate **312**. Various leads are used to electronically connect microelectronic element **350** to various other features of microelectronic assembly **310**. For example, lead **380** electrically connects microelectronic element **350** to conductive features of substrate **312**, and lead **382** electrically connects microelectronic element **350** to microelectronic element **322**. Further, wire bond **384**, which can be similar in structure to various ones of wire bonds **332**, is used to form a contact surface **386** on the surface **344** of encapsulation layer **342** that electrically connected to microelectronic element **350**. This can be used to directly electrically connect a feature of another microelectronic assembly to microelectronic element **350** from above encapsulation layer **342**. Such a lead could also be included that is connected to microelectronic element **322**, including when such a microelectronic element is present without a second microelectronic element **350** affixed thereon. An opening (not shown) can be formed in encapsu-

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lation layer **342** that extends from surface **344** thereof to a point along, for example, lead **380**, thereby providing access to lead **380** for electrical connection thereto by an element located outside surface **344**. A similar opening can be formed over any of the other leads or wire bonds **332**, such as over wire bonds **332C** at a point away from the ends **336C** thereof. In such an embodiment, ends **336C** can be positioned beneath surface **344**, with the opening providing the only access for electrical connection thereto.

FIG. 6 shows a stacked package of microelectronic assemblies **410** and **488**. In such an arrangement solder masses **452** electrically and mechanically connect end surfaces **438** of assembly **410** to conductive elements **440** of assembly **488**. The stacked package can include additional assemblies and can be ultimately attached to contacts **492** on a PCB **490** or the like for use in an electronic device. In such a stacked arrangement, wire bonds **432** and conductive elements **430** can carry multiple electronic signals therethrough, each having a different signal potential to allow for different signals to be processed by different microelectronic elements, such as microelectronic element **422** or microelectronic element **489**, in a single stack.

In the exemplary configuration in FIG. 6, wire bonds **432** are configured with a curved portion **448** such that at least some of the ends **436** of the wire bonds **432** extend into an area that overlies a major surface **424** of the microelectronic element **422**. Such an area can be defined by the outer periphery of microelectronic element **422** and extending upwardly therefrom. An example of such a configuration is shown from a view facing toward first surface **414** of substrate **412** in FIG. 18, where wire bonds **432** overlie a rear major surface of the microelectronic element **422**, which is flip-chip bonded at a front face **425** thereof to substrate **412**. In another configuration (FIG. 5), the microelectronic element **422** can be mounted face-up to the substrate **312**, with the front face **325** facing away from the substrate **312** and at least one wire bond **336** overlying the front face of microelectronic element **322**. In one embodiment, such wire bond **336** is not electrically connected with microelectronic element **322**. A wire bond **336** bonded to substrate **312** may also overlie the front or rear face of microelectronic element **350**. The embodiment of microelectronic assembly **410** shown in FIG. 18 is such that conductive elements **428** are arranged in a pattern forming a first array in which the conductive elements **428** are arranged in rows and columns surrounding microelectronic element **422** and may have a predetermined pitch between individual conductive elements **428**. Wire bonds **432** are joined to the conductive elements **428** such that the respective bases **434** thereof follow the pattern of the first array as set out by the conductive elements **428**. Wire bonds **432** are configured, however, such that the respective ends **436** thereof can be arranged in a different pattern according to a second array configuration. In the embodiment shown the pitch of the second array can be different from, and in some cases finer than that of the first array. However, other embodiments are possible in which the pitch of the second array is greater than the first array, or in which the conductive elements **428** are not positioned in a predetermined array but the ends **436** of the wire bonds **432** are. Further still, conductive elements **428** can be configured in sets of arrays positioned throughout substrate **412** and wire bonds **432** can be configured such that ends **436** are in different sets of arrays or in a single array.

FIG. 6 further shows an insulating layer **421** extending along a surface of microelectronic element **422**. Insulating layer **421** can be formed from a dielectric or other electrically insulating material prior to forming the wire bonds. The insulating layer **421** can protect microelectronic element from

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coming into contact with any of wire bonds **423** that extend thereover. In particular, insulating layer **421** can avoid electrical short-circuiting between wire bonds and short-circuiting between a wire bond and the microelectronic element **422**. In this way, the insulating layer **421** can help avoid malfunction or possible damage due to unintended electrical contact between a wire bond **432** and the microelectronic element **422**.

The wire bond configuration shown in FIGS. 6 and 18 can allow for microelectronic assembly **410** to connect to another microelectronic assembly, such as microelectronic assembly **488**, in certain instances where the relative sizes of, for example, microelectronic assembly **488** and microelectronic element **422** would not otherwise permit. In the embodiment of FIG. 6 microelectronic assembly **488** is sized such that some of the contact pads **440** are in an array within an area smaller than the area of the front or rear surface **424** or **426** of the microelectronic element **422**. In a microelectronic assembly having substantially vertical conductive features, such as pillars, in place of wire bonds **432**, direct connection between conductive elements **428** and pads **440** would not be possible. However, as shown in FIG. 6, wire bonds **432** having appropriately-configured curved portions **448** can have ends **436** in the appropriate positions to make the necessary electronic connections between microelectronic assembly **410** and microelectronic assembly **488**. Such an arrangement can be used to make a stacked package where microelectronic assembly **418** is, for example, a DRAM chip or the like having a predetermined pad array, and wherein microelectronic element **422** is a logic chip configured to control the DRAM chip. This can allow a single type of DRAM chip to be used with several different logic chips of varying sizes, including those which are larger than the DRAM chip because the wire bonds **432** can have ends **436** positioned wherever necessary to make the desired connections with the DRAM chip. In an alternative embodiment, microelectronic package **410** can be mounted on printed circuit board **490** in another configuration, where the unencapsulated surfaces **436** of wire bonds **432** are electrically connected to pads **492** of circuit board **490**. Further, in such an embodiment, another microelectronic package, such as a modified version of package **488** can be mounted on package **410** by solder balls **452** joined to pads **440**.

Additional arrangements for microelectronic packages having multiple microelectronic elements are shown in FIGS. 31A-C. These arrangements can be used in connection with the wire bond arrangements shown, for example in FIG. 5 and in the stacked package arrangement of FIG. 6, discussed further below. Specifically, FIG. 31A shows an arrangement in which a lower microelectronic element **1622** is flip-chip bonded to conductive elements **1628** on the surface **1614** of substrate **1612**. The second microelectronic element **1650** is face-up mounted on top of the first microelectronic element **1622** and connected through wire bonds **1688** to additional conductive elements **1628**. FIG. 31B shows an arrangement where a first microelectronic element **1722** is face-up mounted on surface **1714** and connected through wire bonds **1788** to conductive elements **1728**. Second microelectronic element **1750** is flip-chip mounted on top of first microelectronic element **1722** through a set of contacts **1726** of the second microelectronic element **1750** which face and are joined to corresponding contacts on the front face of the first microelectronic element **1722**. These contacts on the first microelectronic element **1722** in turn can be connected through circuit patterns of the first microelectronic element **1722** and be connected by some of the wire bonds **1788** to the conductive elements **1728** on substrate **1712**.



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FIG. 31C shows an arrangement where first **1822** and second **1850** microelectronic elements are mounted side-by-side on surface **1814** of substrate **1812**. Either one or both of the microelectronic elements (and additional microelectronic elements) can be mounted in the face-up or flip-chip configurations described herein. Further, any of the microelectronic elements employed in such an arrangement can be connected to each other through circuit patterns on one or both such microelectronic elements or on the substrate or on both, which electrically connect respective conductive elements **1828** to which the microelectronic elements are electrically connected.

FIG. 7 shows a microelectronic assembly **10**, of the type shown in FIG. 1 with a redistribution layer **54** extending along surface **44** of encapsulation layer **42**. As shown in FIG. 7, traces **58** are electrically connected to inner contact pads **61** which are electrically connected to end surfaces **38** of wire bonds **32** and extend through the substrate **56** of redistribution layer **54** to contact pads **60** exposed on surface **62** of substrate **56**. An additional microelectronic assembly can then be connected to contact pads **60** by solder masses or the like. A similar structure to redistribution layer **54** can extend along second surface **16** of substrate **12** in what is known as a fan-out layer. A fan-out layer can allow microelectronic assembly **10** to connect to an array of a different configuration than the conductive element **40** array would otherwise permit.

FIGS. 8A-8E show various configurations that can be implemented in the structure of or near the ends **36** of wire bonds **32** in a structure similar to FIGS. 1-7. FIG. 8A shows a structure in which a cavity **64** is formed in a portion of encapsulation layer **42** such that an end **36** of wire bond **32** projects above a minor surface **43** of the encapsulation layer at cavity **64**. In the embodiment shown, end surface **38** is positioned below major surface **44** of encapsulation layer **42**, and cavity **64** is structured to expose end surface **38** at surface **44** to allow an electronic structure to connect thereto. Other embodiments are possible wherein end surface **38** is substantially even with surface **44** or is spaced above surface **44**. Further, cavity **64** can be configured such that a portion of edge surface **37** of wire bond **32** near the end **36** thereof can be uncovered by encapsulation layer **42** within cavity **64**. This can allow for a connection to wire bond **32** from outside of assembly **10**, such as a solder connection, to be made from both end surface **38** and the uncovered portion of edge surface **37** near end **36**. Such a connection is shown in FIG. 8B and can provide a more robust connection to a second substrate **94** using a solder mass **52**. In an embodiment cavity **64** can have a depth beneath surface **44** of between about 10  $\mu\text{m}$  and 50  $\mu\text{m}$  and can have a width of between about 100  $\mu\text{m}$  and 300  $\mu\text{m}$ . FIG. 8B shows a cavity having a similar structure to that of FIG. 8A, but with tapered side walls **65**. Further, FIG. 8B shows a second microelectronic assembly **94** electrically and mechanically connected to wire bond **32** by a solder mass **52** at a contact pad **96** exposed at a surface of a substrate **98** thereof.

Cavity **64** can be formed by removing a portion of encapsulation layer **42** in the desired area of cavity **64**. This can be done by known processes including, laser etching, wet etching, lapping or the like. Alternatively, in an embodiment where encapsulation layer **42** is formed by injection molding, cavity **64** can be formed by including a corresponding feature in the mold. Such a process is discussed in U.S. Pat. App. Pub. No. 2010/0232129, which is hereby incorporated by reference in its entirety. The tapered shape of cavity **64** shown in FIG. 8B can be the result of a particular etching process used in its formation.

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FIGS. 8C and 8E show end structures that include a substantially rounded end portion **70** on wire bond **32**. Rounded end portion **70** is configured to have a cross-section that is wider than the cross-section of the portion of wire bond **32** between base **34** and end **36**. Further rounded end portion **70** includes an edge surface **71** that extends outward from the edge surface **37** of wire bond **32** at the transition therebetween. The incorporation of a rounded edge portion **70** can act to secure wire bond **32** within encapsulation layer **42** by providing an anchoring feature wherein the change in direction of the surface **71** gives encapsulation layer **42** a location to surround end **70** on three sides. This can help prevent wire bond **32** from becoming detached from conductive elements **28** on substrate **12**, resulting in a failed electrical connection. Additionally, the rounded end portion **70** can provide increased surface area that is uncovered by encapsulation layer **42** within surface **44** to which an electronic connection can be made. As shown in FIG. 8E, rounded end portion **70** can extend above surface **44**. Alternatively, as shown in FIG. 8C, rounded end portion **70** can further, be ground or otherwise flattened to provide a surface that is substantially flush with surface **44** and can have an area greater than the cross-section of wire bond **32**.

A rounded end portion **70** can be formed by applying localized heat in the form of a flame or a spark at the end of the wire used to make wire bond **32**. Known wire bonding machines can be modified to carry out this step, which can be done immediately after cutting the wire. In this process, the heat melts the wire at the end thereof. This localized portion of liquid metal is made round by the surface tension thereof and is retained when the metal cools.

FIG. 8D shows a configuration for microelectronic assembly **10** where end **36** of wire bond **32** includes a surface **38** that is spaced above major surface **44** of encapsulation layer **42**. Such a configuration can present benefits similar to that discussed with respect to cavity **64**, above, specifically, by providing a more robust connection with a solder mass **68** that wicks along the portion of edge surface **37** that is uncovered by encapsulation layer **42** above surface **44**. In an embodiment, end surface **38** can be spaced above surface **44** at a distance of between about 10  $\mu\text{m}$  and 50  $\mu\text{m}$ . Additionally, in the embodiment of FIG. 8D and any of the other embodiments in which a portion of edge surface **37** is uncovered by encapsulation layer **42** above a surface of encapsulation layer **42**, the end can include a protective layer formed thereon. Such a layer can include an oxidation protection layer, including those made from gold, an oxide coating or an OSP.

FIG. 9 shows an embodiment of microelectronic assembly **10** with a stud bump **72** formed on end surface **38** of wire bond **32**. Stud bump **72** can be formed after making microelectronic assembly **10** by applying another, modified wire bond on top of end surface **44** and optionally extending along a portion of surface **44**. The modified wire bond is cut or otherwise severed near the base thereof without drawing out a length of wire. Stud bumps **72** containing certain metals may be applied directly to ends **38** without first applying a bonding layer such as a UBM, thus providing way of forming conductive interconnects to bond pads which are not directly wettable by solder. This can be useful when wire bond **32** is made from a non-wettable metal. In general, stud bumps consisting essentially of one or more of copper, nickel, silver, platinum and gold can be applied this way. FIG. 9 shows a solder mass **68** formed over stud bump **72** for electronic or mechanical connection to an additional microelectronic assembly.

FIGS. 10A-10D show configurations for ends **36** of wire bonds **32** that include a bent or curved shape. In each embodiment, end **36** of wire bond **32** is bent such that a portion **74**

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thereof extends substantially parallel to surface 44 of encapsulation layer 42 such that at least a portion of edge surface 76 is not covered by, for example, major surface 44. This portion of edge surface 37 can extend upwards outside of surface 44 or can be ground or otherwise flattened so as to extend substantially flush with surface 44. The embodiment of FIG. 10A includes an abrupt bend in wire bond 32 at the portion 74 of end 36 that is parallel to surface 44 and terminates in an end surface 38 that is substantially perpendicular to surface 44. FIG. 10B shows an end 36 having a more gradual curve near the portion 74 of end 36 that is parallel to surface 44 than that which is shown in FIG. 10A. Other configurations are possible, including those in which a portion of a wire bond according to those shown in FIG. 3, 4, or 5 includes an end with a portion thereof substantially parallel to surface 44 and having a portion of the edge surface thereof uncovered by encapsulation layer 42 at a location within surface 44. Additionally, the embodiment of FIG. 10B includes a hooked portion 75 on the end thereof, which positions end surface 38 below surface 44 within encapsulation layer 42. This can provide a more robust structure for end 36 that is less likely to become dislodged from within encapsulation layer 42. FIGS. 10C and 10D show structures that are, respectively, similar to those shown in FIGS. 10A and 10B, but are uncovered by encapsulation layer 42 at a location along surface 44 by cavities 64 formed in encapsulation layer 42. These cavities can be similar in structure to those discussed above with respect to FIGS. 8A and 8B. The inclusion of ends 36 including a portion 74 thereof that extends parallel to surface 44 can provide increased surface area for connection therewith by virtue of the elongated uncovered edge surface 75. The length of such a portion 74 can be greater than the width of cross-section of the wire used to form wire bond 32.

In a further example shown in FIG. 29, multiple wire bonds 1432 can be joined on a single conductive element 1428. Such a group of wire bonds 1432 can be used to make additional connection points over the encapsulation layer 1442 for electrical connection with conductive element 1428. The exposed portions 1439 of the commonly-joined wire bonds 1432 can be grouped together on surface 1444 of encapsulation layer 1442 in an area, for example about the size of conductive element 1428 itself or another area approximating the intended size of a bonding mass for making an external connection with the wire bond 1432 group. Such wire bonds 1432 can be either ball-bonded, as shown, or edge bonded on conductive element 1428, as described above. The various techniques described herein for severing the metal wire during the wire bonding process, e.g., by laser or other cutting instrument can be employed when forming multiple wire bonds to a conductive element on a substrate.

FIGS. 11-15 show a microelectronic assembly 10 in various steps of a fabrication method thereof. FIG. 11 shows microelectronic assembly 10' at a step where microelectronic element 22 has been electrically and mechanically connected to substrate 12 on first surface 14 and within first region 18, thereof. Microelectronic element 22 is shown in FIG. 11 as being mounted on substrate 12 in a flip-chip arrangement, such as through contacts on microelectronic element 22 which face and are joined to corresponding contacts on a confronting surface 14 of the substrate. For example, the joints between the contacts of the microelectronic element and the substrate can be made through electrically conductive material such as masses 26, e.g., a conductive paste, conductive matrix material, solder masses, and the contacts can be of any suitable configuration such as pads, posts, e.g., micropillars, stud bumps, etc., among others. "Flip-chip bonding", is used herein to mean such arrangement of face-to-face elec-

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trical bonding between corresponding contacts of a microelectronic element and a substrate, or between a microelectronic element and another microelectronic element.

Alternatively face-up wire bonding of the microelectronic element's contacts to the substrate could be used instead, such as seen in the example of FIG. 1. In the embodiment of the method step shown in FIG. 11, a dielectric underfill layer 66 may be provided between microelectronic element 22 and substrate 12.

FIG. 12 shows microelectronic assembly 10" having wire bonds 32 applied on pads 30 of conductive elements 28 exposed on first surface 14 of substrate 12. As discussed, wire bonds 32 can be applied by heating an end of a wire segment to soften the end such that it forms a deposition bond to conductive element 28 when pressed thereto, forming base 34. The wire is then drawn out away from conductive element 28 and manipulated, if desired, in a specified shape before being cut or otherwise severed to form end 36 and end surface of wire bond 32. Alternatively, wire bonds 32 can be formed from, for example, an aluminum wire by wedge bonding. Wedge-bonding is formed by heating a portion of the wire adjacent the end thereof and dragging it along the conductive element 28 with pressure applied thereto. Such a process is described further in U.S. Pat. No. 7,391,121, the disclosure of which is hereby incorporated by reference herein in its entirety.

In FIG. 13 encapsulation layer 42 has been added to microelectronic assembly 10'" by being applied over first surface 14 of substrate, extending upwardly therefrom and along edge surfaces 37 of wire bonds 32. Encapsulation layer 42 also covers underfill layer 66. Encapsulation layer 42 can be formed by depositing a resin over microelectronic assembly 10" shown in FIG. 12. This can be done by placing assembly 10" in an appropriately configured mold having a cavity in the desired shape of the encapsulation layer 42 that can receive assembly 10'. Such a mold and the method of forming an encapsulation layer therewith can be as shown and described in U.S. Pat. App. Pub. No. 2010/0232129, the disclosure of which is incorporated by reference herein in its entirety. Alternatively, encapsulation layer 42 can be prefabricated to the desired shape from an at least partially compliant material. In this configuration, compliant properties of the dielectric material allow encapsulation layer 42 to be pressed into position over wire bonds 32 and microelectronic element 22. In such a step, wire bonds 32 penetrate into the compliant material forming respective holes therein, along which encapsulation layer 42 contacts edge surfaces 37. Further, microelectronic element 22 may deform the compliant material so that it can be received therein. The compliant dielectric material can be compressed to expose end surfaces 38 on outer surface 44. Alternatively, any excess compliant dielectric material can be removed from encapsulation layer to form a surface 44 on which end surfaces 38 of wire bonds 32 are uncovered or cavities 64 can be formed that uncover end surfaces 38 at a location within surface 63.

In the embodiment shown in FIG. 13, encapsulation layer is formed such that, initially, surface 44 thereof is spaced above end surfaces 38 of wire bonds 32. To expose the end surfaces 38, the portion of encapsulation layer 42 that is above end surfaces 38 can be removed, exposing a new surface 44' that is substantially flush with end surfaces 42, as shown in FIG. 14. Alternatively, cavities 64, such as those shown in FIGS. 8A and 8B can be formed in which end surfaces 38 are uncovered by encapsulation layer 42. In a further alternative, encapsulation layer 42 can be formed such that surface 44 is already substantially flush with end surfaces 48 or such that surface 44 is positioned below end surfaces 48, as shown in

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FIG. 8D. Removal, if necessary, of a portion of encapsulation layer 42 can be achieved by grinding, dry etching, laser etching, wet etching, lapping, or the like. If desired, a portion of the ends 36 of wire bonds 32 can also be removed in the same, or an additional, step to achieve substantially planar end surface 38 that are substantially flush with surface 44. If desired, cavities 64 can also be formed after such a step, or stud bumps, as shown in FIG. 10 can also be applied. The resulting microelectronic assembly 10 can then be affixed on a PCB or otherwise incorporated in a further assembly, for example a stacked package, as shown in FIG. 6.

In an alternative embodiment shown in FIG. 15, wire bonds 32 are initially formed in pairs as portions 32' of a wire loop 86. In this embodiment, loop 86 is made in the form of a wire bond as discussed above. The wire segment is drawn upward, then bent and drawn in a direction having at least a component thereof in the direction of the first surface 14 of substrate 13 and to a position substantially overlying an adjacent conductive element 28. The wire is then drawn substantially downward to a position near the adjacent conductive element 28 before being cut or otherwise severed. The wire is then heated and connected to the adjacent conductive element 28 by deposition bonding or the like to form loop 86. Encapsulation layer 42 is then formed so as to substantially cover loop 86. A portion of encapsulation layer 42 is then removed by grinding, etching or the like by a process that also removes a portion of loop 86 such that the loop is severed and divided into its two portions 32', thereby forming wire bonds 32 with end surfaces 38 uncovered by encapsulation layer 42 at a location along surface 44 which is formed on encapsulation layer 42. Subsequent finishing steps can then be applied to assembly 10, as discussed above.

FIGS. 16A-16C show steps in an alternative embodiment for making cavities 64, as discussed above, surrounding ends 36 of wire bonds 32. FIG. 16A shows a wire bond 32, of the general type discussed above with respect to FIGS. 1-6. Wire bond 32 has a mass of sacrificial material 78 applied on end 36 thereof. The sacrificial material mass 78 can be substantially spherical in shape, which can result from the material's surface tension during formation thereof, or other desired shapes that would be understood by a person of ordinary skill in the art. Sacrificial material mass 78 can be formed by dipping the ends 36 of wire bonds 32 in solder paste to coat the ends thereof. The viscosity of the solder paste can be adjusted prior to dipping to control the amount of solder mass that wicking and surface tension cause to adhere to ends 36. This can, accordingly, affect the size of masses 78 that are applied on ends 36. Alternatively, masses 78 can be formed by depositing a soluble material onto the ends 36 of the wire bonds 32. Other possible masses 78 can be individual solder balls or other masses on ends or by other means using other materials, such as copper or gold flashing, used in microelectronic component fabrication, that can later be removed.

In FIG. 16B, a dielectric layer 42 is shown having been added to assembly 10, including upward along edge surfaces 37 of wire bonds 32. The dielectric layer also extends along a portion of the surface of the sacrificial material mass 78, such that it is spaced apart from the end 36 of the wire bond 32 thereby. Subsequently, sacrificial material mass 78 is removed, such as by washing or rinsing in a solvent, melting, chemical etching or other technique, leaving cavity 64 in dielectric layer 42 substantially in the negative shape of mass 78 before removal thereof, and exposing a portion of edge surface 37 near end 36 of wire bond 32.

Alternatively, sacrificial material mass 78 can be formed to coat substantially all of wire bond 32 by extending along the edge surface 37 thereof. This arrangement is shown in FIG.

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17A. Such a coating can be applied over wire bonds 32 after formation on assembly 10, as discussed above, or can be applied as a coating to the wire used to make wire bonds 32. This would, essentially, be in the form of a coated wire or a two-part wire, for example, with an inner core of copper and a solder coating. FIG. 17B shows dielectric layer 42 applied over wire bonds 32 and the sacrificial mass 78 so as to extend along the edge surface 37 of the sacrificial mass 78, thereby spacing apart dielectric layer 42 from wire bond 32 substantially along the length thereof.

FIG. 17C shows the structure that results from removing a portion of the sacrificial material mass 78 to form cavity 64 around end 36 and exposing a portion of edge surface 37. In such an embodiment a majority of, or at least a portion of, the sacrificial material mass 78 can be left in place between dielectric layer 42 and wire bond 32. FIG. 17C further shows a solder mass 52 electrically and mechanically connecting wire bond 32 to a contact pad 40A of another microelectronic structure 10A.

After formation of the wire segment and bonding thereof to a conductive element to form a wire bond, particularly of the ball bond type discussed above, the wire bond (32 in FIG. 1, for example) is then separated from a remaining portion of the wire within the capillary (such as 804 in FIG. 32). This can be done at any location remote from the base 34 of the wire bond 32 and is preferably done at a location remote from the base 34 by a distance at least sufficient to define the desired height of the wire bond 32. Such separation can be carried out by a mechanism disposed within the capillary 804 or disposed outside of the capillary 804, between the face 806 and the base 34 of the wire bond 32. In one method, the wire segment 800 can be separated by effectively burning through the wire 800 at the desired separation point, which can be done by application of a spark or flame thereto. To achieve greater accuracy in wire bond height, different forms of cutting the wire segment 800 can be implemented. As described herein, cutting can be used to describe a partial cut that can weaken the wire at a desired location or cutting completely through the wire for total separation of the wire bond 32 from the remaining wire segment 800.

In one example shown in FIG. 32 a cutting blade 805 can be integrated into the bond head assembly, such as within capillary 804. As shown, an opening 807 can be included in the side wall 820 of the capillary 804 through which cutting blade 805 can extend. The cutting blade 805 can be moveable in and out of the interior of the capillary 804 so that it can alternately allow the wire 800 to freely pass therethrough or engage the wire 800. Accordingly, the wire 800 can be drawn out and the wire bond 32 formed and bonded to a conductive element 28 with the cutting blade 805 in a position outside of the capillary interior. After bond formation, the wire segment 800 can be clamped using a clamp 803 integrated in the bond head assembly to secure the position of the wire. The cutting blade 803 can then be moved into the wire segment to either fully cut the wire or to partially cut or weaken the wire. A full cut can form end surface 38 of the wire bond 32 at which point the capillary 804 can be moved away from the wire bond 32 to, for example, form another wire bond. Similarly, if the wire segment 800 is weakened by the cutting blade 805, movement of the bond head unit with the wire still held by the wire clamp 803 can cause separation by breaking the wire 800 at the area weakened by the partial cut.

The movement of the cutting blade 805 can be actuated by pneumatics or by a servo motor using an offset cam. In other examples the cutting blade 805 movement can be actuated by a spring or a diaphragm. The triggering signal for the cutting blade 805 actuation can be based on a time delay that counts

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down from formation of the ball bond or can be actuated by movement of the capillary **804** to a predetermined height above the wire bond base **34**. Such a signal can be linked to other software that operates the bonding machine so that the cutting blade **805** position can be reset prior to any subsequent bond formation. The cutting mechanism can also include a second blade (not shown) spaced opposite blade **805** to cut the wire from opposing sides thereof.

In another example, a laser **809** can be assembled with the bond head unit and positioned to cut the wire segment. As shown in FIG. **33**, a laser head **809** can be positioned outside of capillary **804** such as by mounting thereto or to another point on the bond head unit that includes capillary **804**. The laser can be actuated at a desired time, such as those discussed above with respect to the cutting blade **805** in FIG. **32**, to cut the wire **800**, forming end surface **38** of the wire bond **32** at a desired height above the base **34**. In other implementations, the laser **809** can be positioned to direct the cutting beam through or into the capillary **804** itself and can be internal to the bond head unit. In an example, a carbon dioxide laser can be used or, as an alternative, a Nd:YAG or a Cu vapor laser could be used.

In another embodiment a stencil **824** as shown in FIGS. **34A-C** can be used to separate the wire bonds **32** from the remaining wire segment **800**. As shown in FIG. **34A**, the stencil **824** can be a structure having a body that defines an upper surface **826** at or near the desired height of the wire bonds **32**. The stencil **824** can be configured to contact the conductive elements **28** or any portions of the substrate **12** between the conductive elements **28**. The stencil includes a plurality of holes **828** that can correspond to the desired locations for the wire bonds **32**, such as over conductive elements **28**. The holes **828** can be sized to accept the capillary **804** of the bond head unit therein so that the capillary can extend into the hole to a position relative to the conductive element **28** to bond the wire **800** to the conductive element, **28** to form the base **34**, such as by ball bonding or the like. The capillary **804** can then be moved vertically out of the hole **828** while drawing out the wire segment to a desired length. Once cleared from the hole **828**, the wire segment can be clamped within the bond head unit, such as by clamp **803**, and the capillary **804** can be moved in a lateral direction (such as parallel to the surface **826** of stencil **824**) to move the wire segment **800** into contact with an edge **829** of the stencil **824** defined by the intersection of the surface of the hole **828** and the outside surface **826** of the stencil **824**. Such movement can cause separation of the wire bond **32** from a remaining portion of the wire segment **800** that is still held within the capillary **804**. This process can be repeated to form the desired number of wire bonds **32** in the desired locations. In an implementation, the capillary can be moved vertically prior to wire separation such that the remaining wire segment projects beyond the face **806** of the capillary **804** by a distance **802** sufficient to form a subsequent ball bond. FIG. **34B** shows a variation of stencil **824** in which the holes **828** are tapered such that they have a diameter that increases from a first diameter at surface **826** to a greater diameter away from surface **826**. In another variation, as shown in FIG. **34C**, the stencil can be formed having an outer frame **821** having a thickness sufficient to space apart surface **826** at the desired distance from substrate **12**. Frame **821** can at least partially surround a cavity **823** configured to be positioned adjacent substrate **12** with a thickness of the stencil **824** extending between the surface **826** and the open area **823** such that the portion of stencil **824** that includes the holes **828** is spaced apart from the substrate **12** when positioned thereon.

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FIGS. **20** and **21** show a further embodiment of a microelectronic assembly **510** in which wire bonds **532** are formed on a lead-frame structure. Examples of lead frame structures are shown and described in U.S. Pat. Nos. 7,176,506 and 6,765,287 the disclosures of which are hereby incorporated by reference herein. In general, a lead frame is a structure formed from a sheet of conductive metal, such as copper, that is patterned into segments including a plurality of leads and can further include a paddle, and a frame. The frame is used to secure the leads and the paddle, if used, during fabrication of the assembly. In an embodiment, a microelectronic element, such as a die or chip, can be joined face-up to the paddle and electrically connected to the leads using wire bonds. Alternatively, the microelectronic element can be mounted directly onto the leads, which can extend under the microelectronic element. In such an embodiment, contacts on the microelectronic element can be electrically connected to respective leads by solder balls or the like. The leads can then be used to form electrical connections to various other conductive structures for carrying an electronic signal potential to and from the microelectronic element. When the assembly of the structure is complete, which can include forming an encapsulation layer thereover, temporary elements of the frame can be removed from the leads and paddle of the lead frame, so as to form individual leads. For purposes of this disclosure, the individual leads **513** and the paddle **515** are considered to be segmented portions of what, collectively, forms a substrate **512** that includes conductive elements **528** in portions that are integrally formed therewith. Further, in this embodiment, paddle **515** is considered to be within first region **518** of substrate **512**, and leads **513** are considered to be within second region **520**. Wire bonds **524**, which are also shown in the elevation view of FIG. **21**, connect microelectronic element **22**, which is carried on paddle **515**, to conductive elements **528** of leads **515**. Wire bonds **532** can be further joined at bases **534** thereof to additional conductive elements **528** on leads **515**. Encapsulation layer **542** is formed onto assembly **510** leaving ends **538** of wire bonds **532** uncovered at locations within surface **544**. Wire bonds **532** can have additional or alternative portions thereof uncovered by encapsulation layer **542** in structures that correspond to those described with respect to the other embodiments herein.

FIGS. **24-26** show a further alternative embodiment of a microelectronic package **810** having closed-loop wire bonds **832**. The wire bonds **832** of this embodiment include two bases **834a** and **834b** that can be joined to adjacent conductive elements **828a** and **828b**, as shown in FIG. **24**. Alternatively, the bases **834a,834b** can both be joined on a common conductive element **828**, as shown in FIGS. **25** and **26**. In such an embodiment, wire bonds **832** define an edge surface **837** that extends between the two bases **834a,834b** in a loop such that the edge surface **837** extends upward in respective portions **837a** and **837b** from the bases to an apex **839** at a surface **844** of the encapsulation layer **842** above the substrate **812**. Encapsulation layer **842** extends along at least some of edge surface portions **837a, 837b**, separating the respective portions from one another, as well as from other wire bonds **832** in package **810**. At apex **839**, at least a portion of the edge surface **837** is uncovered by the encapsulation layer **842**, such that the wire bond **832** is available for electrical interconnection with another component, which can be another microelectronic component or other component, e.g., a discrete element such as a capacitor or inductor. As shown in FIGS. **24-26**, wire bonds **832** are formed such that apex **839** is offset from conductive element **828** in at least one lateral direction across the surface of the substrate **812**. In one example, apex **839** can overlie a major surface of microelectronic element

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820 or otherwise overlie a first region of the substrate 812 with which the microelectronic element 820 is aligned. Other configurations for wire bonds 832 are possible, including configurations in which apex 839 is positioned in any of the locations of the end surfaces of the wire bonds discussed in the other embodiments. Further, apex 839 can be uncovered within a hole, such as shown in FIG. 8A. Still further, apex 839 can be elongated and can be uncovered on surface 844 extending over a length thereof, as shown with respect to the edge surfaces in FIGS. 10A-10D. By providing a connection feature in the form of the uncovered edge surface 837 surrounding apex 839 that is supported a wire bond 832 extending between two bases 834a, 834b, rather than one, more accurate placement of the connection feature in the directions defined by major surface 844 can be achieved.

FIGS. 27 and 28 show a variation of the embodiment of in FIGS. 24-26, in which bond ribbons 934 are used in place of wire bonds 834. Bond ribbons can be a generally flat piece of conductive material, such as any of the materials discussed previously for the formation of wire bonds. A bond ribbon structure can be wider than it is thick, in contrast to a wire bond, which can be generally circular in cross section. As shown in FIG. 27, bond ribbons 934 each include a first base 934a that can be bonded extending along a portion of conductive element 928. A second base 934b of ribbon bond 932 can be joined to a portion of first base 934a. Edge surface 937 extends between bases 934a and 934b in two corresponding portions 937a and 937b to apex 939. A portion of edge surface in the area of apex 939 is uncovered by encapsulant 942 along a portion of major surface 944, thereof. Further variations are possible, such as those described with respect to the wire bonds used in the other embodiments disclosed herein.

The structures discussed above can be utilized in construction of diverse electronic systems. For example, a system 711 in accordance with a further embodiment of the invention includes microelectronic assembly 710, as described above, in conjunction with other electronic components 713 and 715. In the example depicted, component 713 is a semiconductor chip whereas component 715 is a display screen, but any other components can be used. Of course, although only two additional components are depicted in FIG. 23 for clarity of illustration, the system may include any number of such components. The microelectronic assembly 710 as described above may be, for example, a microelectronic assembly as discussed above in connection with FIG. 1, or a structure incorporating plural microelectronic assemblies as discussed with reference to FIG. 6. Assembly 710 can further include any one of the embodiments described in FIGS. 2-22. In a further variant, multiple variations may be provided, and any number of such structures may be used.

Microelectronic assembly 710 and components 713 and 715 are mounted in a common housing 719, schematically depicted in broken lines, and are electrically interconnected with one another as necessary to form the desired circuit. In the exemplary system shown, the system includes a circuit panel 717 such as a flexible printed circuit board, and the circuit panel includes numerous conductors 721, of which only one is depicted in FIG. 23, interconnecting the components with one another. However, this is merely exemplary; any suitable structure for making electrical connections can be used.

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The housing 719 is depicted as a portable housing of the type usable, for example, in a cellular telephone or personal digital assistant, and screen 715 is exposed at the surface of the housing. Where microelectronic assembly 710 includes a light-sensitive element such as an imaging chip, a lens 723 or other optical device also may be provided for routing light to the structure. Again, the simplified system shown in FIG. 23 is merely exemplary; other systems, including systems commonly regarded as fixed structures, such as desktop computers, routers and the like can be made using the structures discussed above.

The above-described embodiments and variations of the invention can be combined in ways other than as specifically described above. It is intended to cover all such variations which lie within the scope and spirit of the invention.

Although the invention herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present invention. It is therefore to be understood that numerous modifications may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of the present invention as defined by the appended claims.

What is claimed is:

1. A method of making a microelectronic assembly, comprising:
  - a) bonding a metal wire to a conductive element exposed at a first surface of a substrate, thereby forming a base of a wire bond on the conductive element;
  - b) extending a length of the metal wire through a capillary of a bonding tool;
  - c) cutting the metal wire within the capillary at a location between a clamped portion of the metal wire within the bonding tool and the base to at least partially define an end surface of the wire bond at a predetermined distance from the base of the wire bond;
  - d) forming an end portion at the end surface having a cross-section wider than a cross-section of the wire bond; and
  - e) forming a dielectric encapsulation layer overlying the first surface of the substrate and defining a major surface spaced apart from the first surface, wherein the encapsulation layer is formed so as to at least partially cover the first surface of the substrate and a portion of the wire bond, such that an unencapsulated portion of the wire bond is defined by a portion of the end portion, wherein the wire bond has a first edge surface defined between the base and the end portion, the end portion has a second edge surface that extends outward from the first edge surface of the wire bond below the major surface of the dielectric encapsulation layer, and the dielectric encapsulation layer surrounds the second edge surface.
2. The method of claim 1, wherein the end portion has a substantially rounded configuration.
3. The method of claim 1, wherein the end portion has a ball shape.
4. The method of claim 1, wherein the cutting is performed before the forming of the end portion.

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